PHASE I OF A STUDY ON LASER MILSATCOM

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TABLE OF CONTENTS

		PAGE
1.0	INTRODUCTION	1
2.0	CRITERIA FOR COMMUNICATION SYSTEM'S SELECTION	3
3.0	CURRENT R & D SATELLITE LASER COMMUNICATION EFFORT	4
	3.1 Airforce Program	4
	3.2 NASA - Airforce	4
	3.3 Navy	5
4.0	INTRODUCTION TO TERRESTRIAL COMMUNICATIONS CALCULATIONS	7
	4.1 Optimization of Carrier-to-Noise Ratio	7
5.0	ANALYSIS OF A NUMBER OF POSSIBLE COMMUNICATION SYSTEMS	21
	5.1 He-Ne Laser Communication System	21
	5.2 Nd:YAG Laser Communication Systems	25
	5.2.1 Nd:YAG Laser Operating in the cw Mode	25
	5.2.2 Nd:YAG Laser Operating in the Q-Switch Mode	27
	5.2.3 Nd:YAG Laser Working at the 2nd Harmonic	30
	5.3 CO_2 Laser Communication Systems	33
	5.3.1 CO_2 Laser Operating in the cw Mode	33
	5.3.2 CO_2 Laser Operating in the Pulsed Mode	36
	5.3.3 CO_2 Laser Operating in the TEA Mode	41
	5.3.4 CO_2 Laser System Operating in the Heterodyne Mode	41
	5.4 Summary of System Analysis	46
6.0	PRICING ESTIMATES AND ANALYSIS	52
7.0	SUMMARY OF ADVANTAGES AND DISADVANTAGES	54
8.0	RECOMMENDATION OF FINAL SYSTEM	56
9.0	PRELIMINARY DESIGN AND PREDICTED PERFORMANCE FOR RECOMMENDED SYSTEM	57
10.0	LASER COMMUNICATION FACILITY REQUIREMENTS	62
11.0	OVER THE HORIZON COMMUNICATION	65
	11.1 Geometry for Optical Scattering Propagation Experiment	66
	11.2 Sample Calculations for Laser Communication via Aerosol Scattering	69
	11.3 Results	72
	11.3.1 System 1	72
	11.3.2 System 2	74
	11.4 Conclusions to Over the Horizon Communication Experiments	76
ACKNOWLEDGEMENT		78
REFERENCES		79

1.0 INTRODUCTION

The potentials of laser communication has been recognized since the development of the laser, back in 1960. Its extremely high carrier frequency and high collimation possibilities make the laser a natural candidate for satellite-to-satellite communication as well as for other special applications such as satellite-to-earth and ground links.

A number of countries have recognized this potential very early on and are attempting to reap the benefit of this new technology by engaging in serious R&D in the field. As can be expected, the U.S. is one of the leaders and is presently involved in many aspects of laser communication for civilian and military uses.

DND has decided to initiate a program of its own to contribute eventually to the R&D work in laser communication undertaken by the U.S. and its allies.

This report will detail a feasibility study of a number of possible laser communication systems that would be used on a first experimental link to be built and installed at CRC. This would be a first step to an eventual contribution towards our Allies' overall effort.

A number of laser links are first examined in relation to their projected performances as a function of range and other parameters. Both digital and T.V. transmissions are described.

Detailed analysis is made, however, on the projected CRC link with a range of 16 km. A comparison of performances and estimated prices is obtained for the most likely candidates.

These results are used as the basis for the final recommendations of a system which is then analysed in greater detail. A number of facility requirements at the link terminals are determined. The link recommended is so chosen that it can be expanded at a later date, into an improved version.

The report ends with the investigation of possible over-the-horizon experiments based on higher power lasers.

2.0 CRITERIA FOR COMMUNICATION SYSTEM'S SELECTION

A number of criteria were considered to permit the laser communication system's selection. These are:

1) The system should have relevance to international activity in this field.
2) It should exemplify the fundamental aspects of laser communications.
3) The technique used should be applicable to satellite communication systems.
4) The system should be expandable into a more sophisticated system as funds become available and technology advances.
5) It should permit propagation measurements.
6) It should provide a facility for an eventual scattering experiment.
7) It should be versatile to provide a laser communication test bed facility where new techniques and subsystems could be tried.
8) It should act as a laser communication learning facility.

These criteria should be considered taking into account budgetary and time constraints.

3.0 CURRENT R & D SATELLITE LASER COMMUNICATION EFFORT

A number of projects on laser communication systems for near-earth and space applications are being carried out in the United States. We shall now give a very brief overview of some of the major projects undertaken in the U.S.

3.1 Airforce Program

A major program that was started more than 10 years ago concerned the development of a space Nd:YAG laser communication system. Most of the systems in development are brassboard proof-of-concept designs. The aim of the program is to show feasibility of laser communication in rates of up to 1 Gb/s. Space-to-space, space-to-aircraft and space-to-ground communications have been considered conceptually. For high performance, the frequency doubled Nd:YAG wavelength of 532 nm is preferred. This permits very small size beamwidths for small size optics. Much work has been done on the development of the laser, modulators and receivers. Complex acquisition and tracking systems are being perfected. The protocol required to go into an acquisition mode and then, after acquisition, into a tracking mode automatically is being optimized. A major effort has yet to be expanded into transforming the brassboards into packages that would meet size/weight/power requirements for space use.

Although the Nd:YAG laser is the primary choice at this point, a CO_2 laser communication system is still considered as a backup system.

3.2 NASA - Airforce

Another major project which started back in the late 1960's, is based on a CO_2 laser communication system for space application. Typical space missions envisaged include satellite-to-satellite, low-orbit-to-synchronous, synchronous-to-synchronous and space-to-ground laser communication systems.

Major advantages of the CO_2 laser system include high reliability and life, as well as very high efficiency of the laser itself, running up to 15%; advanced modulator and detector technology, and, in general, a mature I.R. technology.

As in the case of the Nd:YAG system, many facets of the communication system are being investigated. This includeslaser improvement, wider bandwidths, better detectors etc. A system in the 300 Mbs range is being investigated. Waveguide lasers are contemplated because of their small size and wide bandwidth. This latter aspect is important for a local oscillator if Doppler shift tracking is required. Finally, acquisition and tracking and the associated protocol are also being tackled both conceptually and experimentally.

3.3 Navy

The U.S. navy is particularly interested in submarine communication as well as ship-to-ship, ship-to-shore and over-the-horizon communication.

Major problems still exist for secure and reliable communication with the submarine fleet. One of the possible solutions envisaged is communication to submarine via a satellite laser communication system. This could take the form,for instance,of a laser in a satellite beaming down to the submerged submarine or a powerful ground transmitter beaming to a satellite which, in turn, would relay the beam down to the submarine by means of a mirror which would re-direct the beam in the required direction. The advantage of this latter mode of operation would be that no restriction need be put on the weight, size and power consumption on the ground based laser.

To penetrate sea water, a laser in the green part of the spectrum is required. Some of the candidates include, argon, mercury-bromide, and xenon-chloride lasers. Development work is still required for the latter two lasers. The exact wavelength required depends, in part on the actual location in the ocean where communication has to be established.

The navy has also been involved in CO_2 laser communication systems for ship-to-ship and ship-to-shore communication. The CO_2 laser is appealing for this type of communication because of the relatively good penetration capability of the CO_2 laser wavelength through haze and light fog.

Finally, the navy is involved in a number of over-the-horizon laser communication experiments. Typical ranges of 63 km and 128 km have been tried.

4.0 INTRODUCTION TO TERRESTRIAL COMMUNICATIONS CALCULATIONS

Before going into a detailed calculation on a specific communications link, such as the CRC link to be considered here, it would be profitable to describe link calculations in a more general way first. This will highlight some of the effect of parameters such as range on communications performance. Once a specific range is selected, the range contribution to the overall system performance becomes hidden in the calculations thus depriving one of an insight into its effects. Also, it could be of interest to investigate other potentials that can be expected from a laser link such as, TV transmission.

4.1 Optimization of Carrier-to-Noise Ratio

To be specific, the system to be analysed is depicted diagrammatically in Fig. 1. The transmitter is made up of a laser emitting a beam which is made to pass in turn through a phase shifter for optical bias optimization, a lens systems to focus it through an electrooptic modulator crystal and a telescope to collimate the beam. The modulation applied to the modulator crystal originates from either a T.V. or digital signal. A driver is used to bring up the voltage to the level required by the crystal.

The receiver consists of a receiving telescope, a high quality detector, a demodulator and a signal receiver (a T.V. monitor or digital receiver).

For high quality T.V. reception, we are considering a AM-FM modulation/ demodulation format - namely a FM analog signal modulating a AM subcarrier.

He-Ne System

As one example, let us consider a system based on a He-Ne laser such as one that we have built and used ourselves in a laser link.[1] In that case, the laser of Fig. 1 is a He-Ne laser (4mW) while the detector is an avalanche detector such as the RCA # C30818.

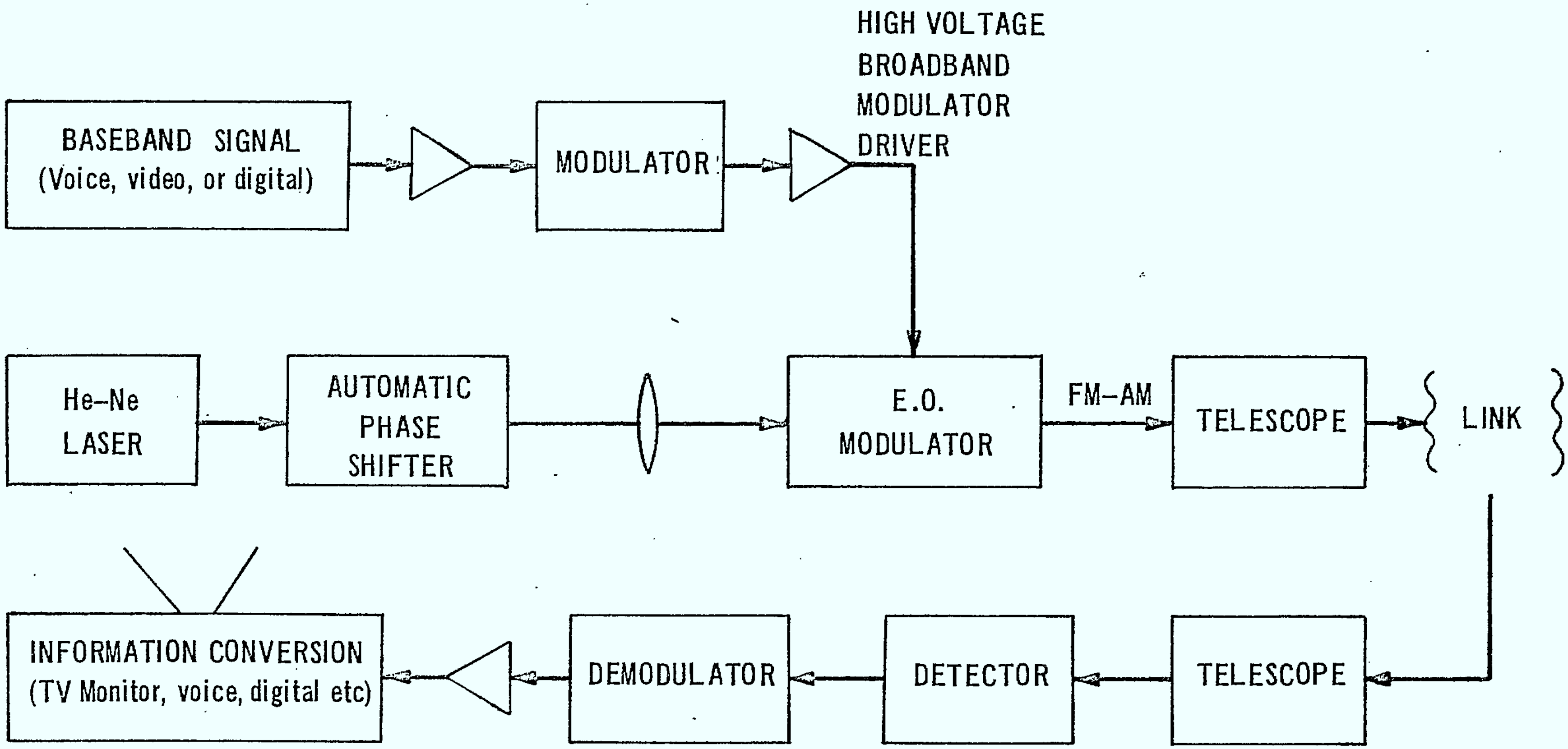

Fig. 1: Laser Communication System

The C/N is one of the most important parameters describing the quality of the system. It is found that the C/N for such a system is given by: (2)

$$\frac{C}{N} = \frac{(P_R \sin(\Gamma_b) J_1(\Gamma_m) R_o M)^2/2}{\left\{2q\left\{I_{ds} + \left(\frac{P_R}{2}\left[1-\cos(\Gamma_b)J_o(\Gamma_m)\right]R_o + I_{db}\right)\left[k_e M + \left(2 - \frac{1}{M}\right)(1 - k_e)\right] M^2\right\} + \frac{4KT}{R_L}\right\} B}$$

where

P_R is the received laser power

R_o unity-gain responsivity

M gain ($M = 1$ in the case of nonmultiplying photodiode)

q electronic charge

I_{ds} that component of the dark current (usually the surface component) which is not multiplied, typically $I_{ds} \approx 10^{-7}$ for an RCA # C30817 diode

I_{db} that component of the dark current (usually the bulk-generated dark current) which undergoes multiplication, $I_{db} = 10^{-10}$ A for this diode

B system bandwidth

R_L load resistance

K_e is an effective weighted ionization rate ratio and depends on the particular diode. It is equal to 0.02 for the RCA # C 30817

$$R_o = \frac{q\eta}{h\nu}$$

where η is the efficiency of the diode
h is Plank's constant
ν is the laser frequency
J_o is the Bessel function of order 0
J_1 " " " " " " 1
Γ_b is the optical bias phase shift
Γ_m is the amplitude of the optical phase shift modulation

It is evident that for best systems performance, one should strive to maximize the C/R at the receiving end. Usually, the driving voltage limitation sets a limit on the driving phase Γ_m . In a real situation, the laser beam power will be attenuated by the intervening optics and atmosphere between laser and detector. In the calculation of C/R, we shall therefore set the received power P_R and the driving phase Γ_m as the independent variables. Optimization will then result by choosing the dc bias Γ_b and gain M so as to make the C/R a maximum.

Because of the complexity of the above relation optimization has to be carried out using a computer. The avalanche diode considered here is well-proven «reach-through» diode of a type such as an RCA # C 30817. The standard load of $R_L = 50\Omega$ is used for the computation and a bandwidth of 30 MHz is assumed. The results of the optimization calculations are plotted in Fig. 2 where the optimum C/R is plotted as a function of the received power P_R for various modulation drive Γ_m. It can be seen that the amount of drive can have a marked effect on the C/R. In fact, a factor of about 9 in Γ_m (which is equivalent to the same factor in drive voltage) will produce a ratio of about 30 in C/R.

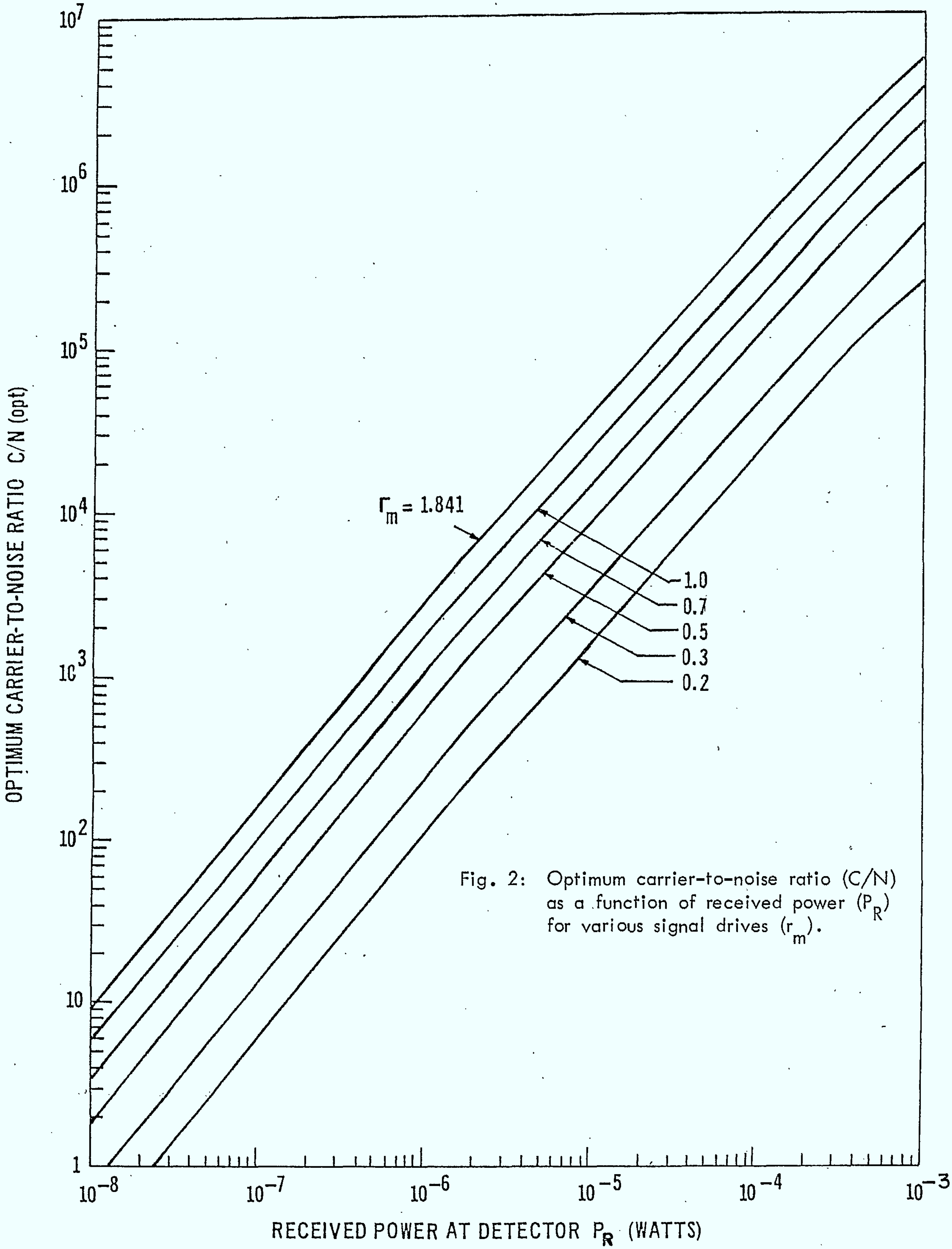

Fig. 2: Optimum carrier-to-noise ratio (C/N) as a function of received power (P_R) for various signal drives (r_m).

To obtain the optimum C/R for any other bandwidth than 30 MHz, simply multiply the C/R by 30 MHz and divide by the required bandwidth B.

Although Fig. 2 can be used to calculate C/R once the receiver power P_R is known, it is possible to go one step further and plot the C/R or S/R as a function of range. To do that, it is required to evaluate the total losses as caused by the transmitter optics, the diffraction effect through the atmosphere, the atmospheric attenuation and, finally the receiver optics.

If T.V. transmission is considered first, optimization can be carried out as a function of range. Figure 3, is the result of such optimization given in the form of the final T.V. image S/R (peak-to-rms in dB) as a function of range for the following parameters:

P_L = 4 mW

R_o = .357 A/W

η = .7

Transmitter optics diameter = .20 m

Receiver optics diameter = .20 m

Transmitter optics attenuation = 1.5 dB

Receiver optics attenuation = 1.5 dB

Γ_m = .61

Pre-amp noise figure = 2 dB

Baseband bandwidth = 4.2 MHz

Frequency deviation (FM) = 4 MHz

Pre-emphasis & weighting factor = 12.8 dB

On the same graph is plotted the threshold above which the received signal will produce an excellent picture (45 dB as per TASO). It is seen that, in principle at least, an excellent T.V. picture could be expected up to about 50 km provided the atmospheric attenuation was not more than .5 dB/km. On

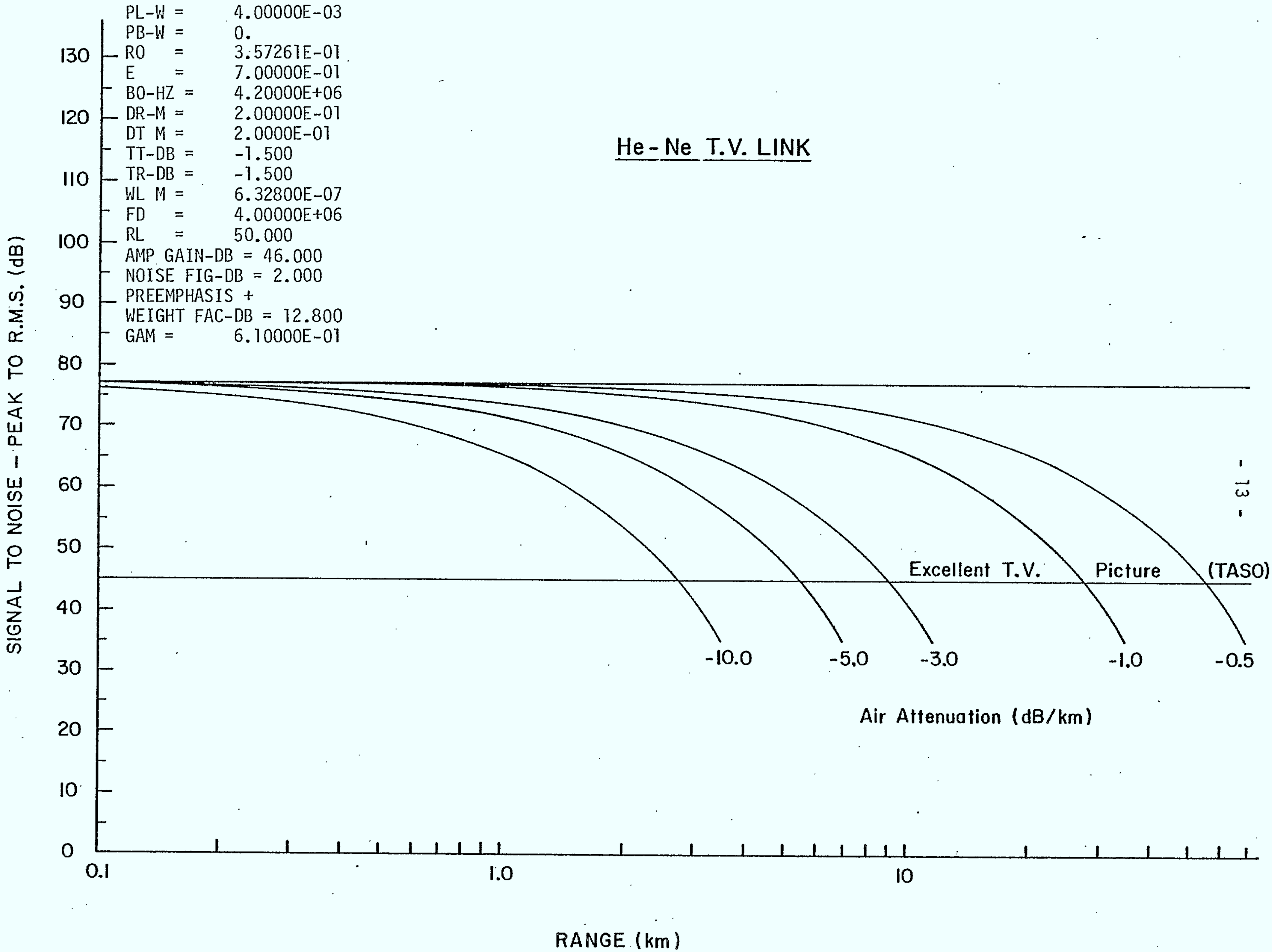

Fig. 3: T.V. performance as a function of range for various atmospheric attenuations.

the other hand, at the 16 km range of interest to the CRC link, the permissible attenuation is of the order of 3 dB/km.

We have obtained experience on the transmission of T.V. signal on a downtown He-Ne laser link in Montreal between two building. Excellent colour pictures could be received for a wide number of weather conditions as described in Ref. 1.

Similar results can be obtained with digital signal transmission. The result for a 1.544 Mb/s system is shown in Fig. 4. Here the SNR (peak-to-peak/r.m.s. - dB) is plotted as a function of range for the same parameters as before. On the same graph are added the levels at which the error-bit rate are 1 part in 10^6 and 1 part in 10^8 respectively. It is seen that performance giving 1 part in 10^6 can be obtained to 50 km, with an attenuation of 1 dB/km. Also, at 16 km, attenuation of up to about 2.6 dB/km can be sustained while still keeping the same performance.

<u>CO_2 Laser System</u>

As a second example, we shall now consider a system based on a CO_2 laser that we have also built and measured its performance.[3] In this case, the laser of Fig. 1 is a CO_2 laser (5 W) and for the receiver a mercury-cadmium-telluride detector is employed.

When a laser beam is modulated by a signal applied to an electrooptic modulator it can be shown easily that the C/N is given by[3]

$$C/N = \frac{\eta \left[P_R \sin(\Gamma_b)\, J_1(\Gamma_m)\right]^2}{\left[2h\nu \left\{P_R \left[1-\cos(\Gamma_b)\, J_o(\Gamma_m)\right] + P_B\right\} + \eta\, (NEP)^2\right] . B}$$

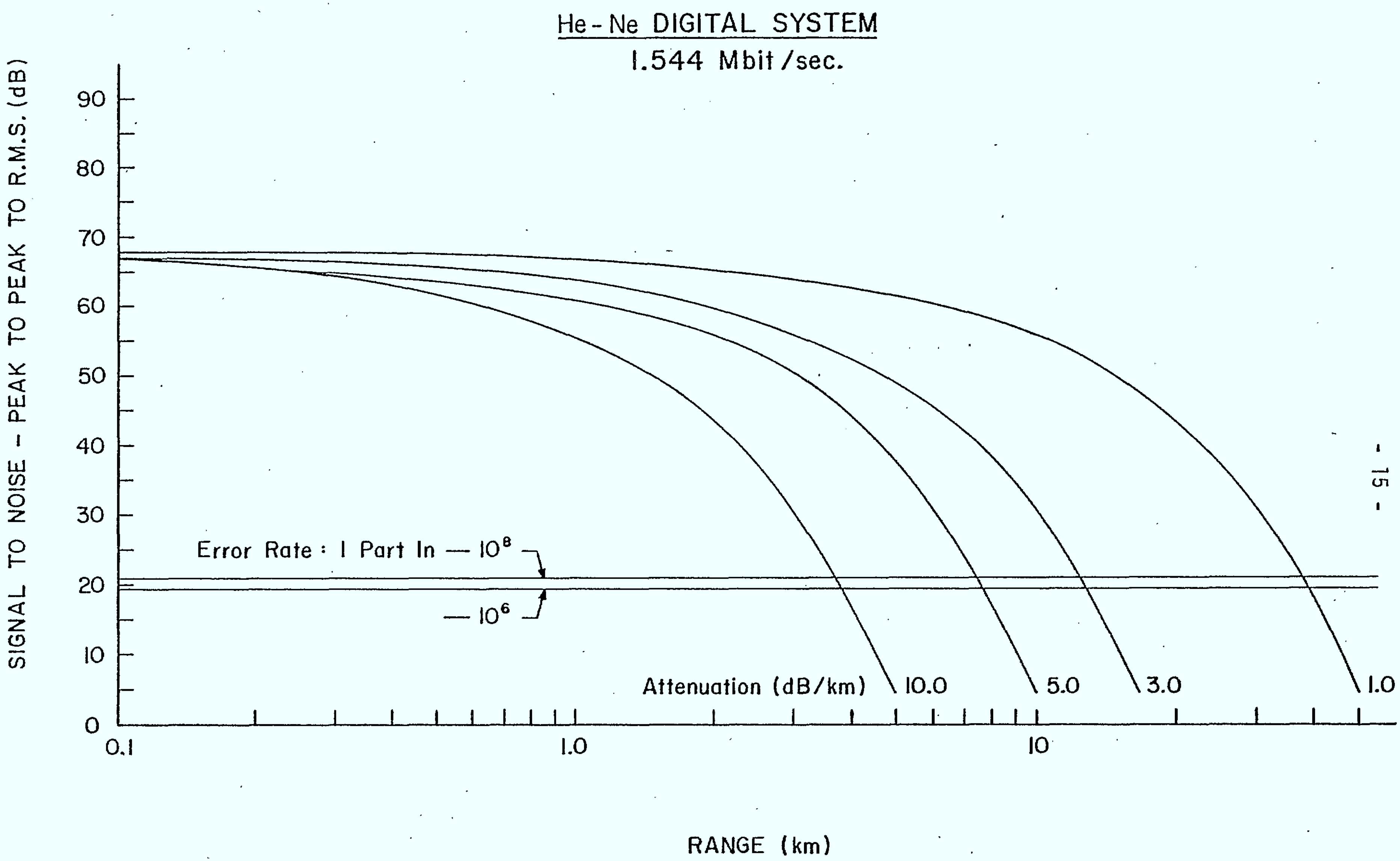

Fig. 4: Performance of a He-Ne digital system as a function of range for various atmospheric attenuations.

where η is the efficiency of the detector

Γ_b is the optical bias phase difference

Γ_m is the optical drive phase difference

J_o, J_1 are the Bessel functions of order 0 and 1

h is Planck's constant

ν is the optical frequency

P_B is the background radiation

B is the front-end bandwidth of the system

NEP the noise-equivalent power of the detector

It is evident that to maximize the C/R for a given Γ_m, it is important to optimize the value of the optical bias Γ_b.

An analysis can be performed as before where optimum SNR is obtained as a function of range. In the case of T.V. signal, we shall assume, as before, that the transmitter and receiver optics is .20m, and the optical attenuation is 1.5 dB for each. The results are plotted in Fig. 5 for η = .10, and Γ_m = .25.

It is seen that an excellent T.V. picture can be obtained for ranges up to 50 km at an atmospheric attenuation of .5 dB/km. At 16 km, on the other end, such a picture could be obtained for attenuation of up to 2.5 dB/km.

A similar calculation was made for a digital system at 1.544 Mb/s. The results are shown in Fig. 6. Attenuation of up to 3 dB/km could be sustained to a range of 16 km while at .5 dB/km, good performance could be expected up to a range of 70 km.

Propagation Statistics

All the results given before take on their real meaning only when they are related to the propagation statistics of a given area. It is possible then to assign a probability of occurrence of a given performance.

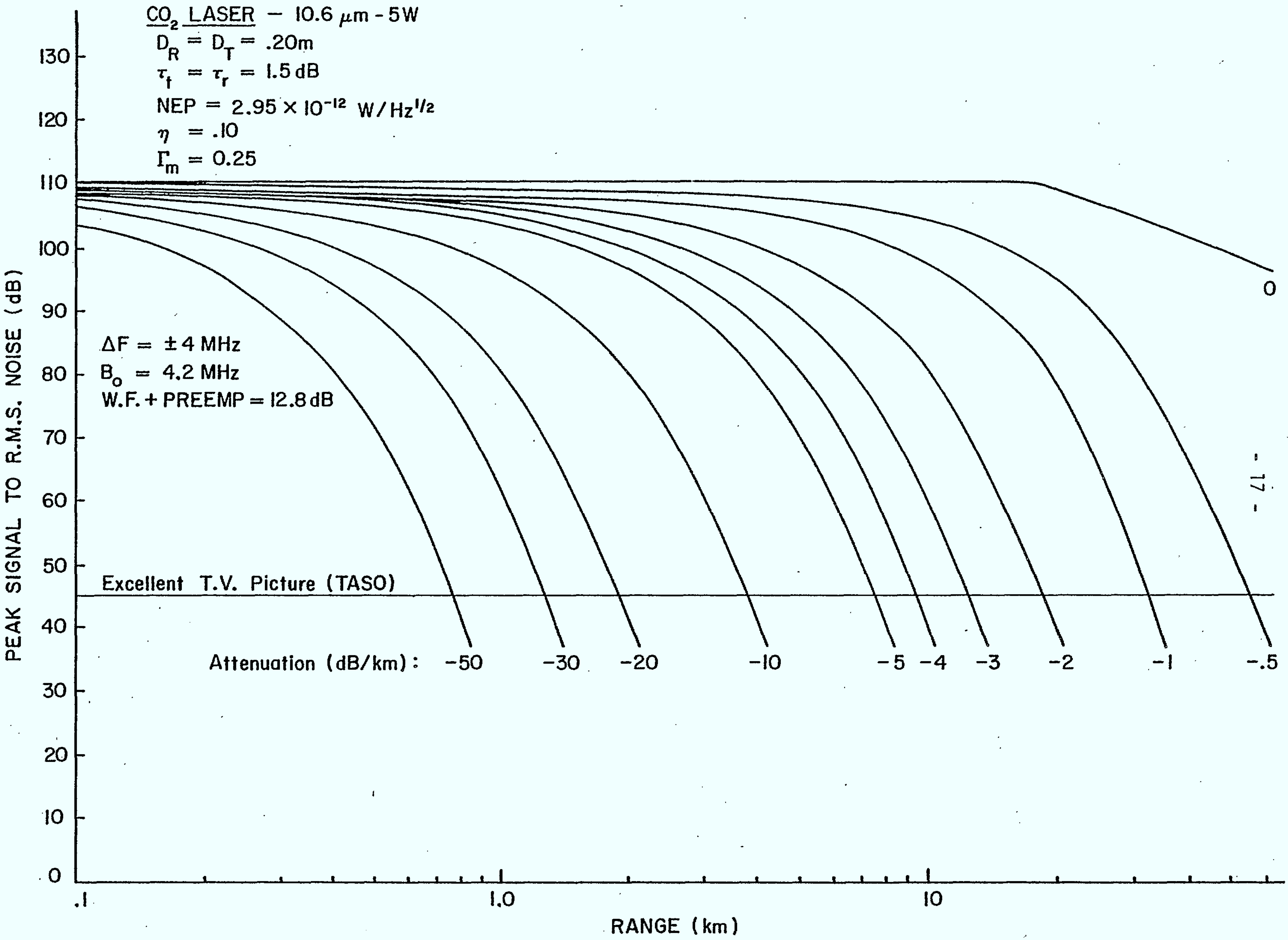

Fig. 5: T.V. performance for a CO_2 laser communication system as a function of range for various atmospheric attenuations.

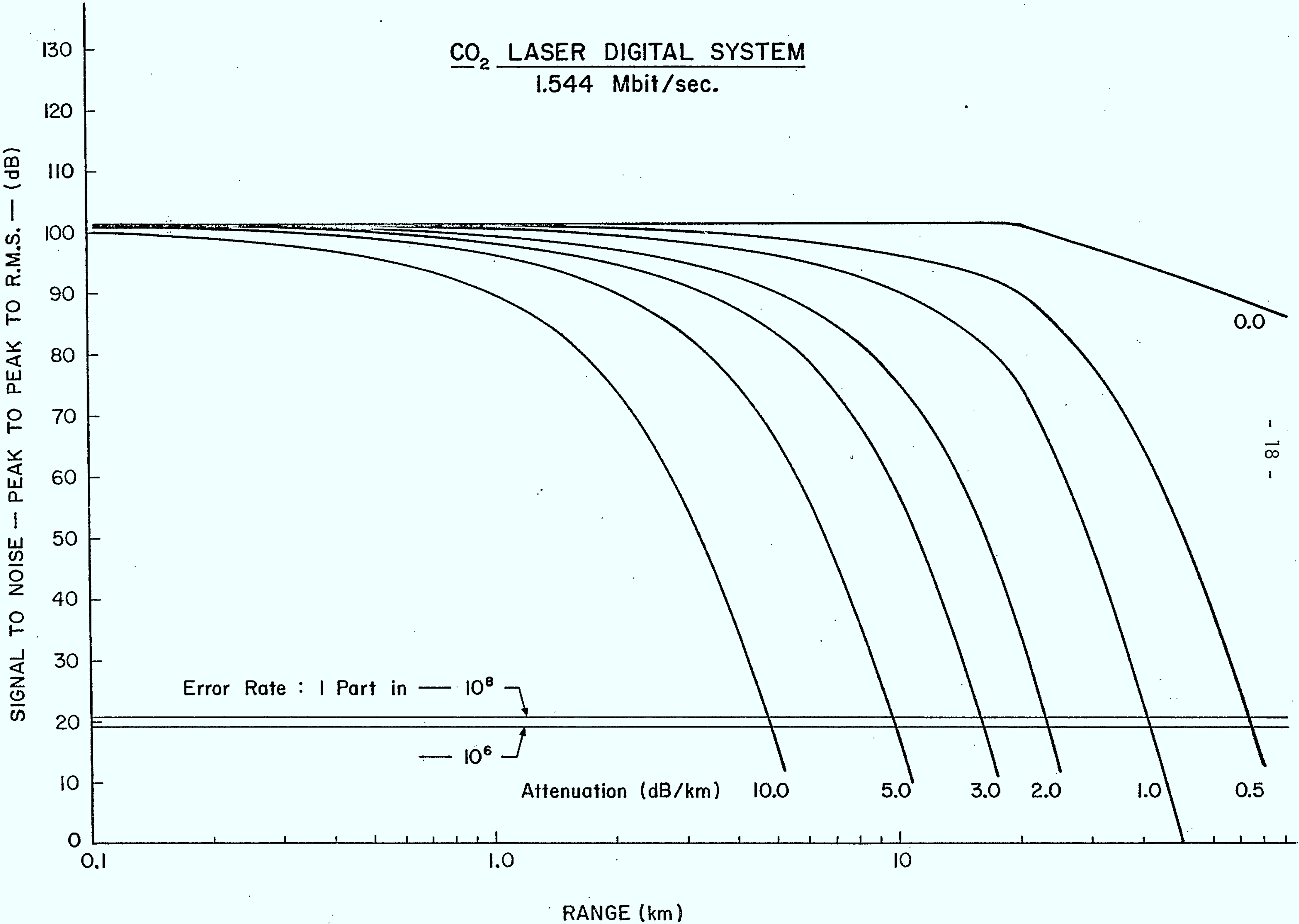

Fig. 6: Performance of a digital CO_2 laser communication system as a function of range for various atmospheric attenuations.

To have a feel for the type of statistics that might be expected around the region of Ottawa, we shall report briefly the results of just such a study that we have made for the region of Montreal back in 1978.[4] Since the meteorological conditions in Montreal are closely related to those of Ottawa (usually displaced by a few hours), it could be relevant to examine such results. In short, a laser propagation study was carried out in the Montreal area using both a He-Ne (0.6328μm) and a CO_2 (10.6μm) laser over a link 1.6 km long. Propagation statistics were obtained over a period of 5 1/2 months that included the winter season. The statistics obtained at the two wavelengths were compared. The statistics represented here (Fig. 7) are for integrated periods where both the He-Ne and CO_2 laser beam were propagated simultaneously (total accumulated time of 1224 hrs.) for the months of January to March 1978. The ordinate shows the percentage of time the attenuation exceeded the abscissa. It is seen, for example, that the probability of occurrence of an attenuation greater than 2 dB/km is 10% for the CO_2 link and 60% for the He-Ne link. Put in other words, the probability that the attenuation is less than 2 dB/km would be 90% for the CO_2 link and 40% for the He-Ne link. On the other hand, the attenuation of the CO_2 and He-Ne beams would be less than 3 dB about 95% and 90% of the time respectively.

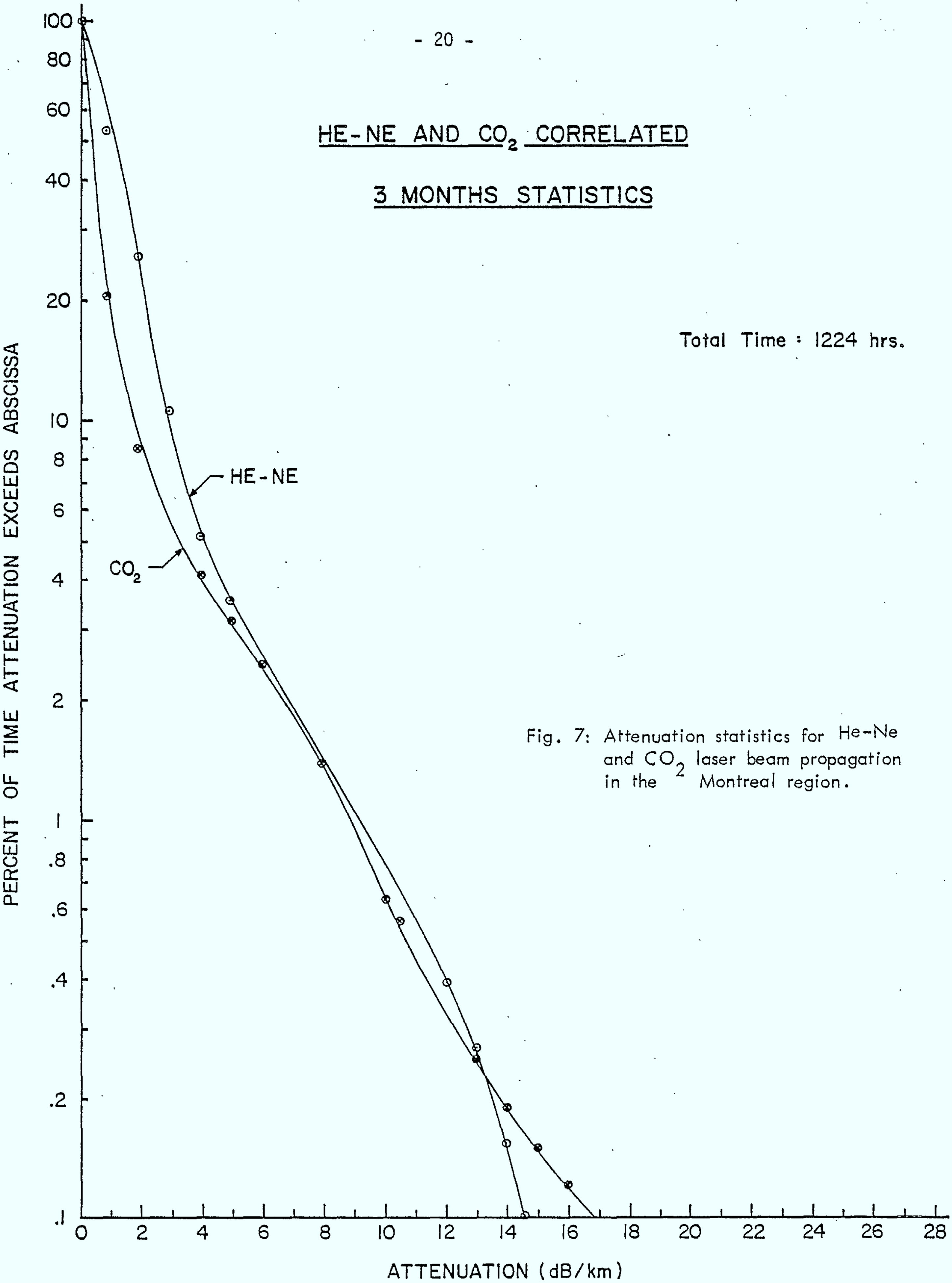

Fig. 7: Attenuation statistics for He-Ne and CO_2 laser beam propagation in the Montreal region.

5.0 ANALYSIS OF A NUMBER OF POSSIBLE COMMUNICATION SYSTEMS

A number of possible systems have been investigated as possible contenders for the CRC link. Systems based on three lasers have been considered. The first involves the He-Ne laser as a source. Although systems based on this laser have shortcomings with respect to the criteria given in Sec. 2 they offer, nevertheless, a major advantage in terms of price while providing a number of interesting features. The second and third group of systems involve the Nd:YAG and CO_2 lasers respectively. Both of them fit more closely the criteria.

Analyses of the various systems were carried out to bring out their salient features and to point out their advantages and disadvantages. The analyses that follow, are all restricted now to the CRC proposed link which is 16 km long. The bit rates of interest (in the RFP) are in the 1 Kbit/s to the 100 Kbit/s range although some examples are also calculated for higher rates.

5.1 He-Ne Laser Communication System

The system to be examined is shown in Fig. 8. On the transmitting side, a small 4 mW cw He-Ne laser is used with the proper matching optics, through an acoustooptic modulator and into a transmitting telescope. To facilitate beam pointing, an electronically activated mirror folds the beam and directs it towards the receiving station. The digital communication signal is applied to a r.f. driver which, in turn modulates the beam by means of the acoustooptic modulator.

At the receiving end, in an analogous fashion to the transmitter, an electronically actuated beam director mirror also folds the beam back into a telescope which captures the transmitted beam. An avalanche detector demodulates the beam and outputs the low frequency signal into a pre-amplifier to be processed by the required electronics. To improve background noise rejection, a narrow band optical filter is placed in front of the detector.

He-Ne Laser Communication System

CW Laser – 1 kbit/100 kbit

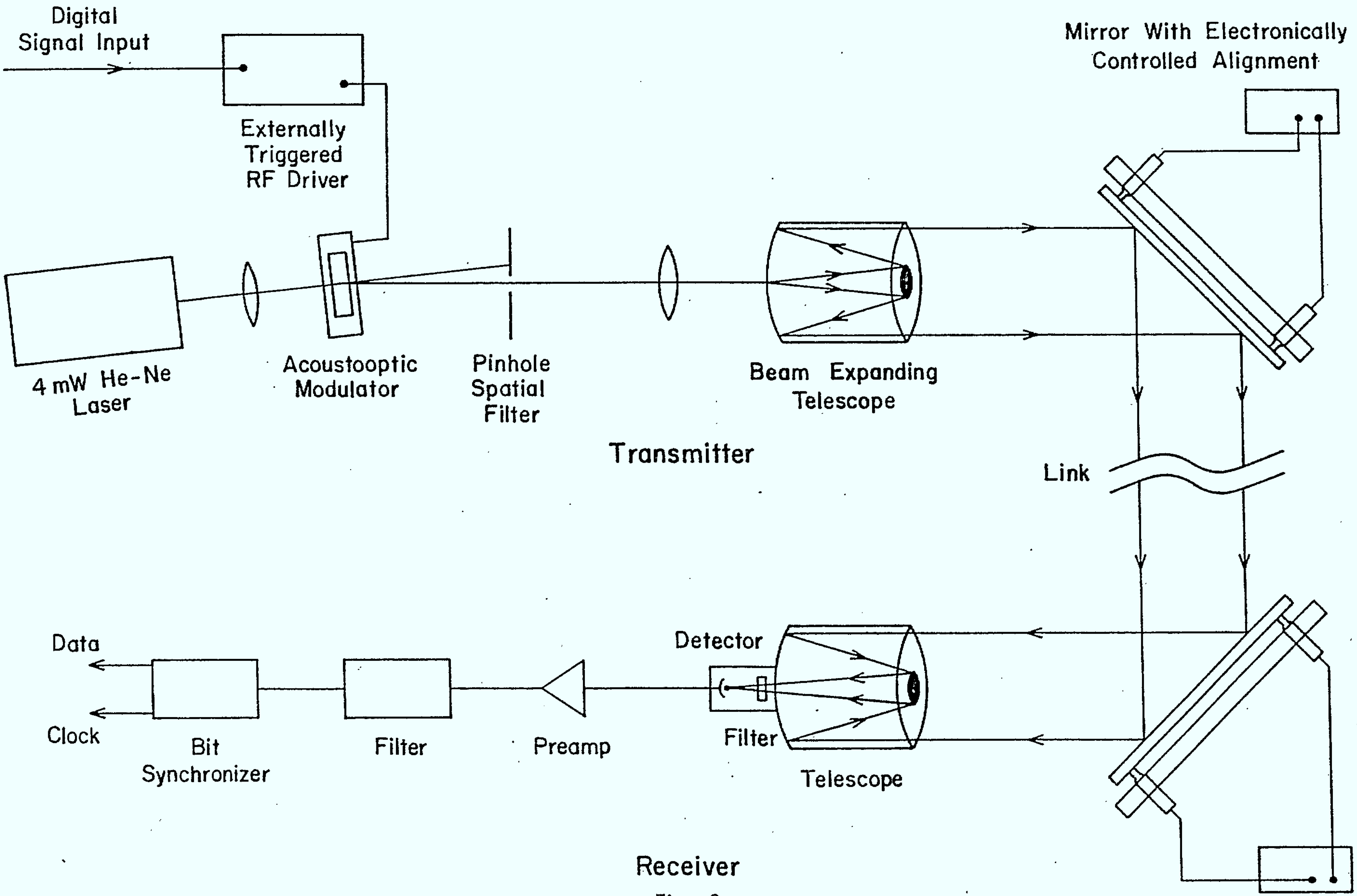

Fig. 8

The assumed parameters are as follows:

Range	16 km
Optics attenuation $T_L = T_R$	1.5 dB
Optics diameter $D_T = D_R$	.20 m
Detector efficiency η	.70
Modulation Index	100%
Pre-amp Noise Figure	2 dB
Wavelength	632.8 nm.

The computer was instructed to maximize the SNR (p.t.p. to r.m.s.) for a 1 Kb/s, 100 Kb/s and 100 Mb/s signal as a function of the transmitted laser power (P_L). This was done to permit an evaluation of the performance of the system using commercially available lasers of specified output powers. The computation was performed as described in the previous section. The resulting curves are as shown in Fig. 9. On the same graph is shown the performance levels at which the expected error bit rates are 1 part in 10^4, 10^6 and 10^8 respectively. It should be stressed, at this point, that the 3 curves depict the performance of the system with no atmospheric attenuation present.

The other losses however, are included in the calculation. These include the optics loss at both ends as well as the loss caused by the spreading of the beam. The beam diameter is adjusted to be 1 m at the receiving end or, that diameter produced by diffraction of the transmitting optics, whichever is greater.

It is seen from the curves for example, that the required laser powers for a performance giving an error bit rate of 1 part in 10^6 are -55 dBm, -44 dBm and -23 dBm for the 1 Kb/s, 100 Kb/s and 100 Mb/s systems respectively.

Since the laser we propose to use has a power of 6 dBm, the margins available for atmospheric attenuation are therefore 61, 50 and 29 dB respectively.

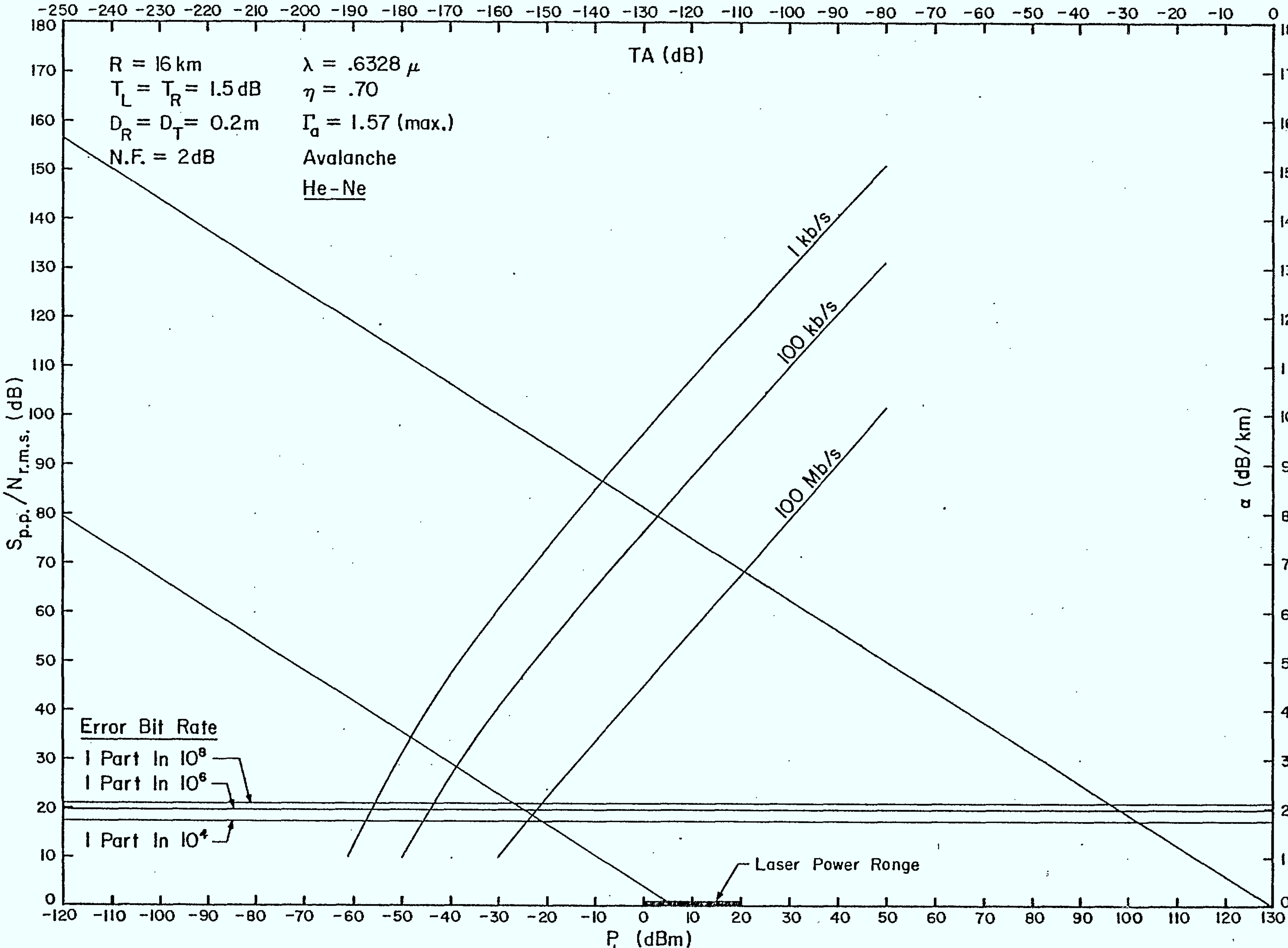

Fig. 9: Performance of a He-Ne laser communication system with envelope detection.

To take atmospheric attenuation into account, we proceed as follows:

A line is drawn in Fig. 9 giving total attenuation T_A over the link as a function of the attentuation factor α (in dB/km) placing the origin at the lower right hand side of the graph. Drawing a line parallel to it and passing through the laser output power (here 6 dBm) will present at the ordinate the amount of attenuation in dB/km that can be sustained over the link for a specified performance.

For example, in the 1 Kb/s system, the -55 dBm requirement for 1 part in 10^6 can be read off that line to correspond to 3.9 dB/km of atmospheric attenuation over the link. In other words, the system would provide a performance better than 1 part in 10^6 for atmospheric attenuation of up to 3.9 dB/km (corresponding to -55 dBm over the 16 km link). In the same way, for the 100 Kb/s and 100 Mb/s case, the maximum attenuation permissible is 3.1 dB/km and 1.8 dB/km respectively.

5.2 Nd:YAG Laser Communication Systems

The Nd:YAG (emitting at 1.06 μm) has a number of possible modes of operation. For each, a communication system is possible. These operations comprise cw, Q switch, mode lock and cavity dump modes. As the last two modes pertain to high repetition rates (1M bit 1G bit) they are beyond the scope of this study. In addition to these modes, it is possible to get the laser to emit at the second harmonic of its wavelength (.53 μm). This mode will also be considered in the analysis.

5.2.1 Nd:YAG Laser Operating in the CW Mode

Such a system is depicted in Fig. 10. The Nd:YAG laser in this case works in the cw mode and has a typical output of say 6 W. The system is then essentially similar to that of the He-Ne laser. An acoustooptic modulator optimized for 1.06 μm would be used for impressing the signal on the laser beam.

Nd:YAG Laser Communication System
CW Laser – 1.06μ – 1kbit/100kbit

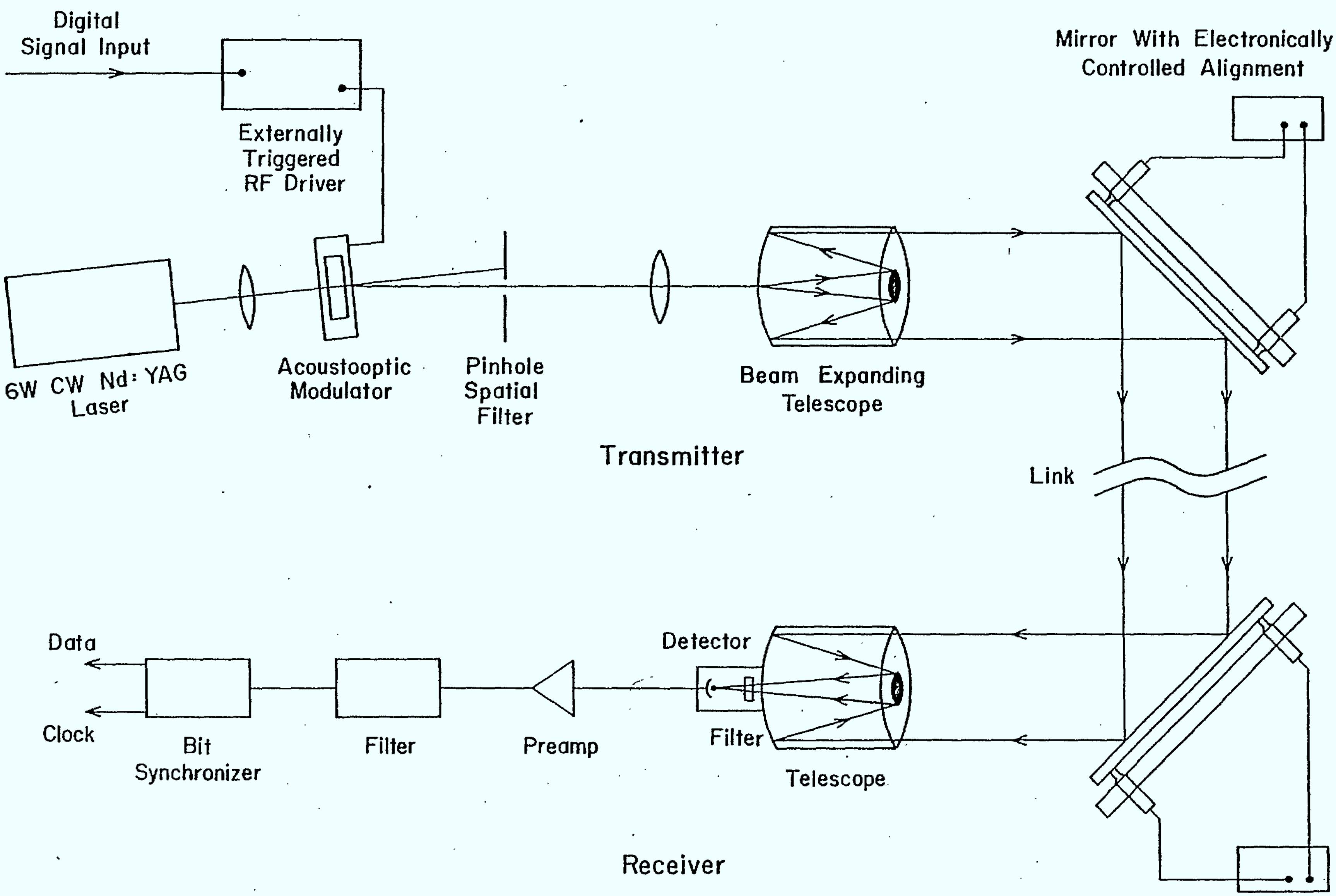

Fig. 10

Similarly, at the receiving end, an avalanche detector optimized for that wavelength would be used. The remainder of the system would be unchanged.

The assumed parameters in the optimization calculation are as follows:

Range	16 km
Optics Attenuation, $T_L = T_R$	1.5 dB
Optics Diameter, $D_T = D_R$	.20 m
Detector Efficiency	15%
Modulation Indes	100%
Pre-amp Noise Figure	2 dB
Wavelength	1.06 μm.

The computer results are given in Fig. 11. Curves are shown for 1 Kb/s, 100 Kb/s and 100 mb/s rates - the last one for comparison purposes only. The attenuation line is drawn for the 6 W CW laser. It is seen that for an error bit rate of 1 part in 10^6, the allowable attenuation over the link is 5.6 dB/km, 4.9 dB/km, 3.5 dB/km for the 1 Kb/s, 100 Kb/s and 100 mb/s rates respectively.

5.2.2 Nd:YAG Laser Operating in the Q-Switch Mode

It is possible to drive a Nd:YAG laser into a Q-switch mode by means of an acoustooptic Q-switcher. When this is done, very high power pulses are possible. Typically, Q-switch operation of a 6 W CW laser would produce pulses of 12 kW with a pulse width of about 100 ns. The system is as shown in Fig. 12. An externally triggered driver is used to Q-switch the laser on command. This can be done up to the maximum allowable repetition rate which, for this mode of operation is about 1 Kb/s with no loss of peak power. Above this level, the peak power falls down rapidly. For example, at 3, 5, 8, 10 Kb/s, the peak power is reduced to 6, 4, 2.5, 2 kW respectively.

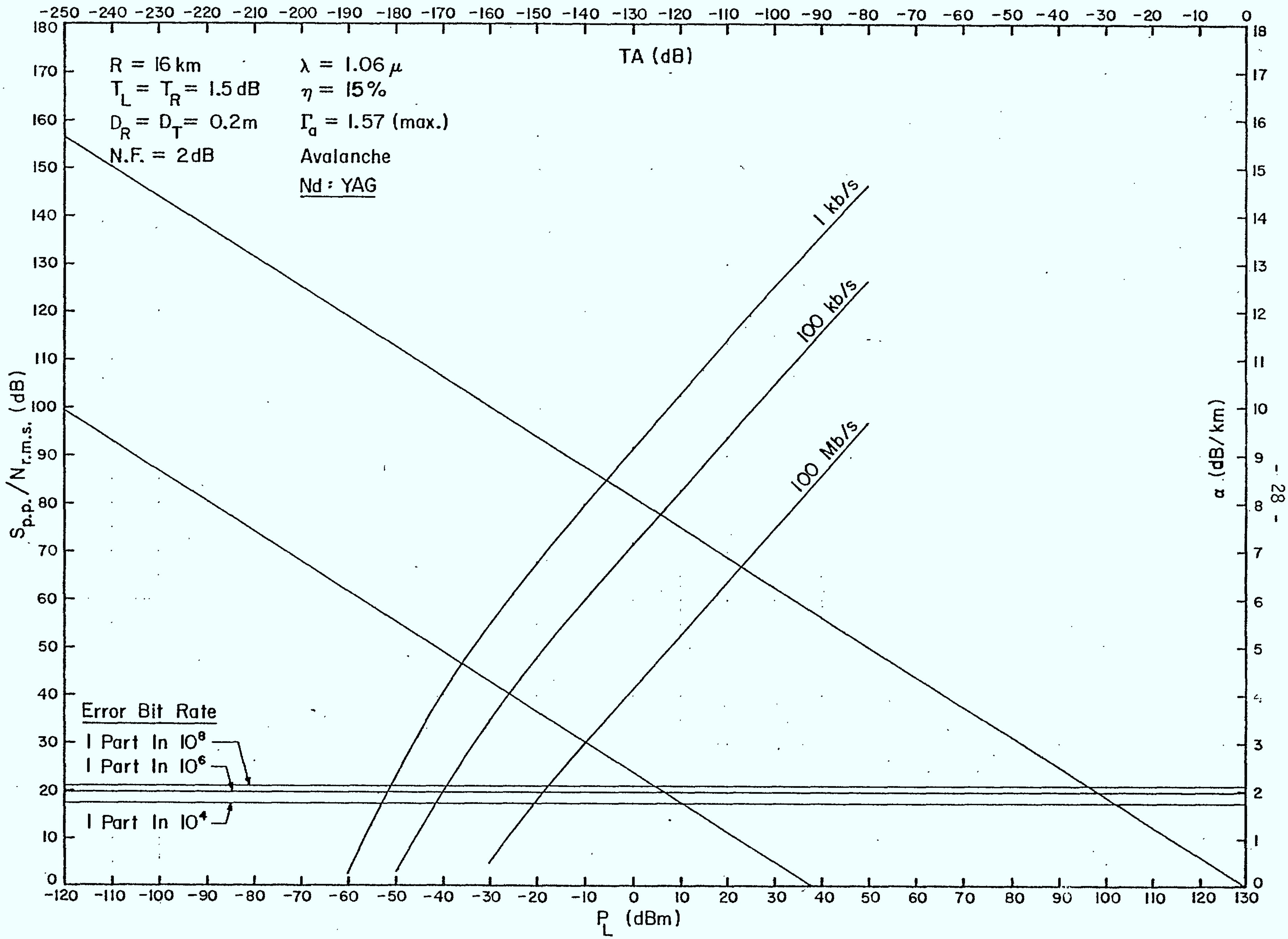

Fig. 11: Performance of a Nd:YAG laser communication system with external modulation and envelope detection.

Nd : YAG Laser Communication System

Q-switched Laser – 1.06 μ – 1kbit

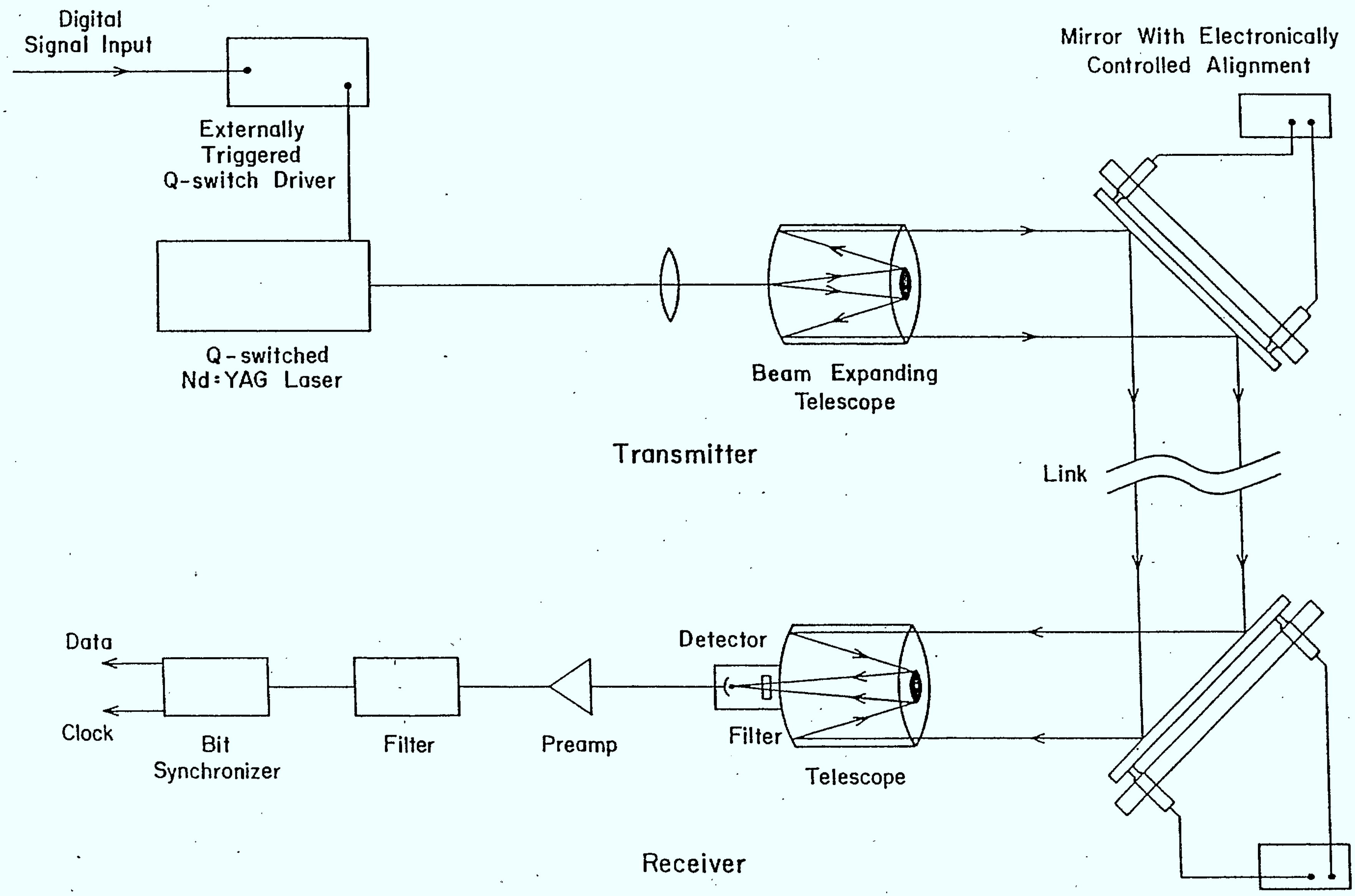

Fig. 12

At the receiving end, the system is essentially that of the cw laser. An exception arises however in the electronic filter requirement. Whereas, in the cw case, the bandwidth of the system is determined essentially by the bit rate, in the Q-switch case, the bandwidth is dictated by the narrow pulse width. This is because the pulse width has an equivalent bandwidth requirement of about 10 MHz - far larger than the bit rate bandwidth needs. Poor utilization is therefore made of the bandwidth capability of the receiver.

Figure 13 depicts the SNR results for the Q-switched pulses. This assumes a synchronous type of detection where the preamplifier is turned on only during expected signal time slots.

The attenuation lines are plotted for the 1 Kb/s and 10 Kb/s Q-switched lasers.

The permissible attenuations for 1 part in 10^6 error signal can be read off as 6. and 5.6 dB/km for the 1 Kb/s and 10 Kb/s respectively.

It is interesting to note that for the 1 Kb/s case, the improvement compared to the cw case is only a nominal one. The cause has been mentioned before and is due to the narrow pulses produced by the Q-switching effect. In fact, this laser channel could support up to 1 Mb/s of information while providing essentially the same performance.

5.2.3 Nd:YAG Laser Working at the 2nd Harmonic

If the Nd:YAG laser is Q-switched and induced to work in the visible (.53 μm) by means of a harmonic generator crystal, power outputs up to 5 kW p.t.p. can be generated at 1 Kb/s and 1 kW up to 10 Kb/s. The system is shown in Fig. 14. The main difference between this system and that operating at 1.06μ is the addition of the harmonic generator. Other differences would include, at the receiving end, a detector and a narrow band filter optimized to that wavelength.

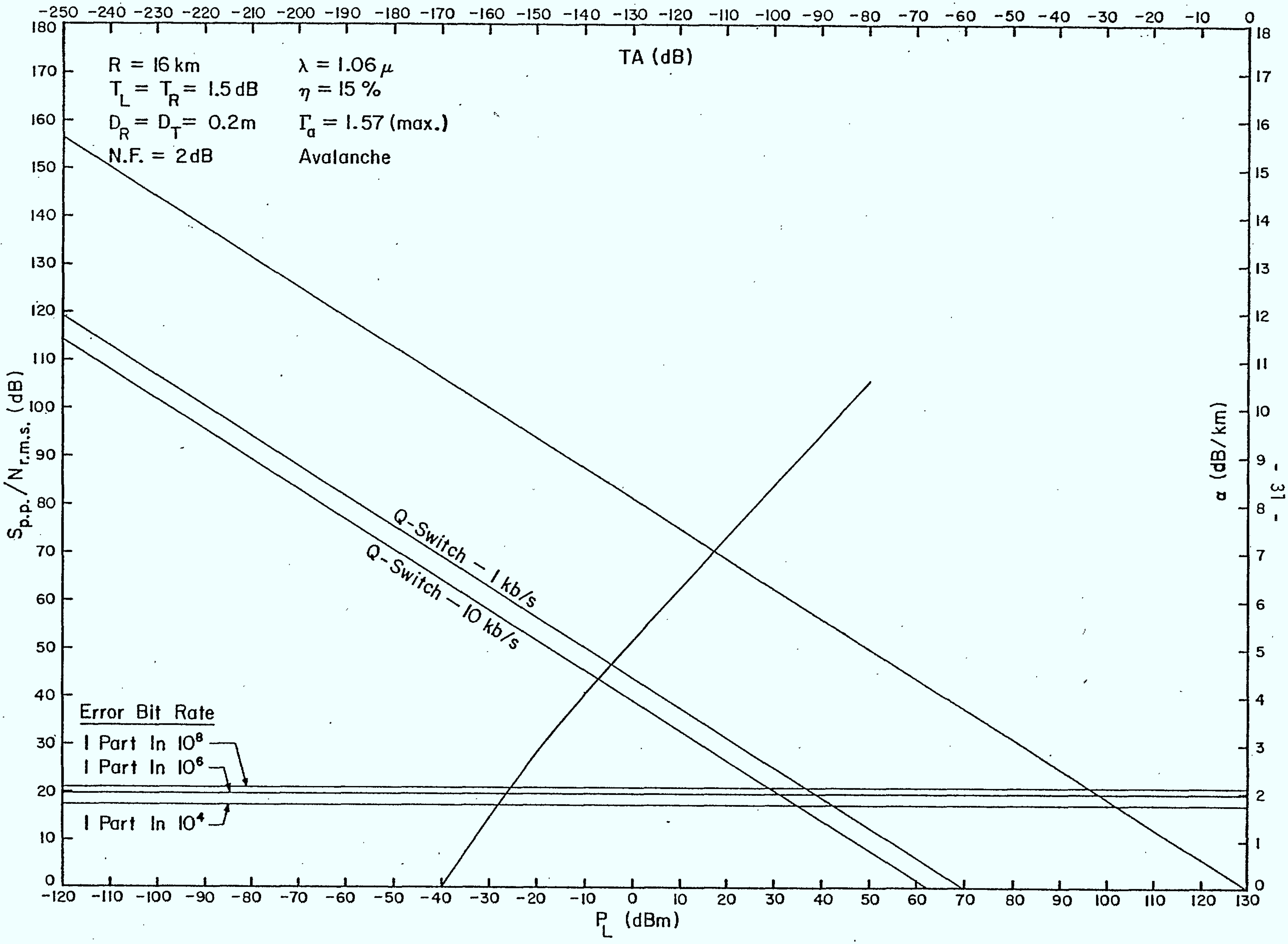

Fig. 13: Performance of a Nd:YAG laser communication system in Q-switch mode and envelope detection.

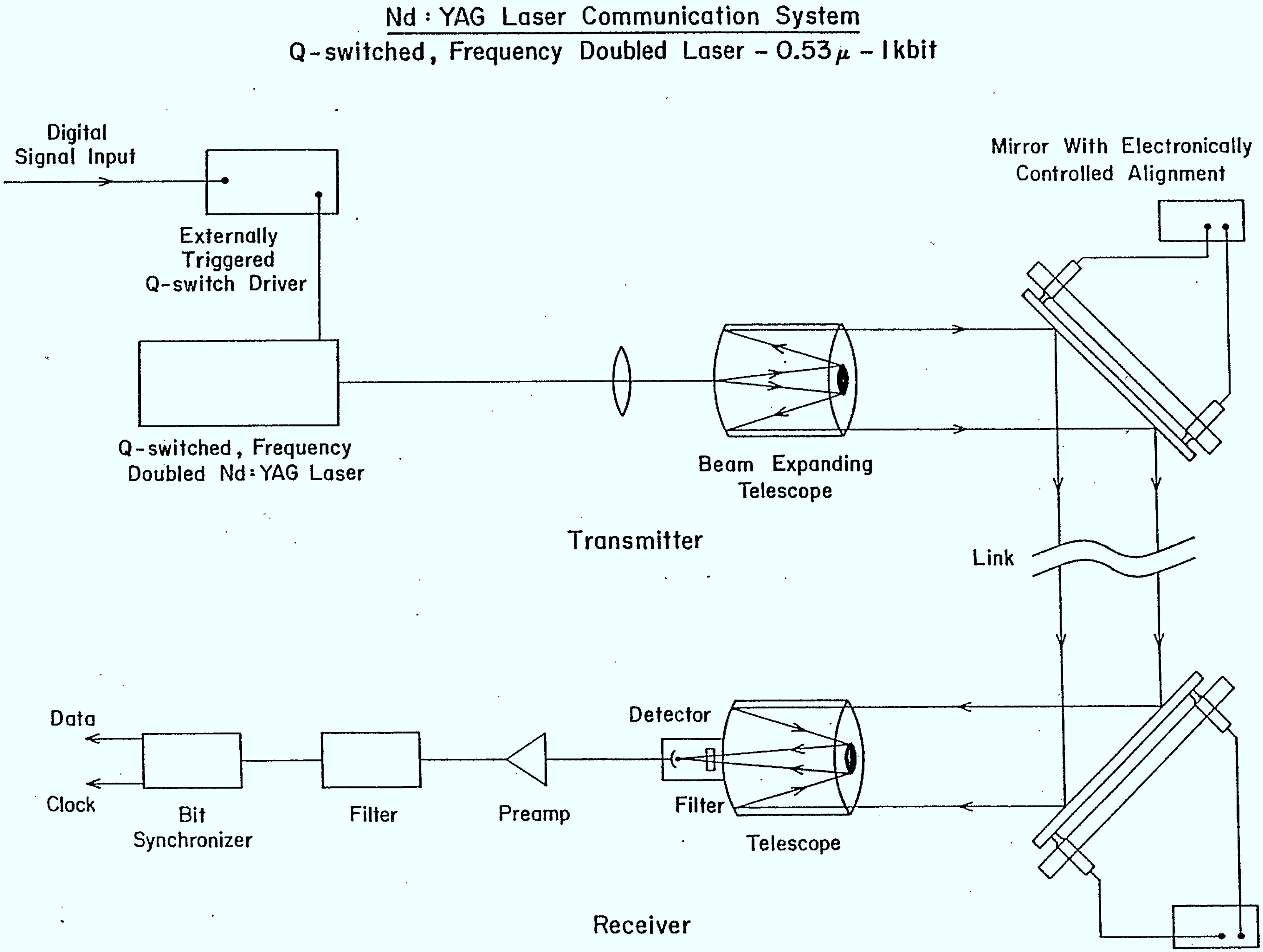
Nd : YAG Laser Communication System
Q-switched, Frequency Doubled Laser – 0.53μ – 1kbit
Digital
Signal Input
Externally
Triggered
Q-switch Driver
Mirror With Electronically
Controlled Alignment
Q-switched, Frequency
Doubled Nd:YAG Laser
Beam Expanding
Telescope
Transmitter
Link
Data
Clock
Bit
Synchronizer
Filter
Preamp
Detector
Filter
Telescope
Receiver

Fig. 14

The computer results for this case is given in Fig. 15 where it is assumed that an avalanche detector is used having a 30% efficiency.

The permissible attenuations for the 1 and 10 Kb/s system at the error rate of 1 part in 10^6 is seen to be 5.8 and 5.3 dB/km respectively.

5.3 CO_2 Laser Communication Systems

Like the Nd:YAG, the CO_2 laser has a number of possible modes of operation. These include operation in the cw, Q-switch, mode-lock and TEA mode. Again, the mode-lock pertains to high repetition rate systems and will not be discussed here. The most common output occurs at the wavelength of 10.6μm.

5.3.1 CO_2 Laser Operating in the cw Mode

The first system considered is very similar conceptually to the other cw laser systems discussed before. Looking at Fig. 16, the modulation is produced by an acoustooptic modulator optimized for 10.6μ. Major differences however, do exist. First, standard optical material usually used in the visible and in the near I.R. cannot be employed at 10.6μm. Typical material making up lenses and other optical components, at these wavelengths, include GaAs, Cd:Te, ZnSe, and Ge. One of the best detectors to be used at 10.6μ is a Hg:Cd:Te detector. For high sensitivity however, this type of detector has to be cooled to liquid nitrogen temperature.

Another addition required is a laser stabilizer to insure that the output emission of the laser occurs at the P20 or any other convenient output line.

The assumed parameters in the optimization calculations are as follows:

Range	16 km
Optics Attenuation, $T_L = T_R$	1.5 dB
Optics Diameter, $D_T = D_R$	.20 m
Modulation Index	100% and $r_a = .25$
Detector Efficiency	10%

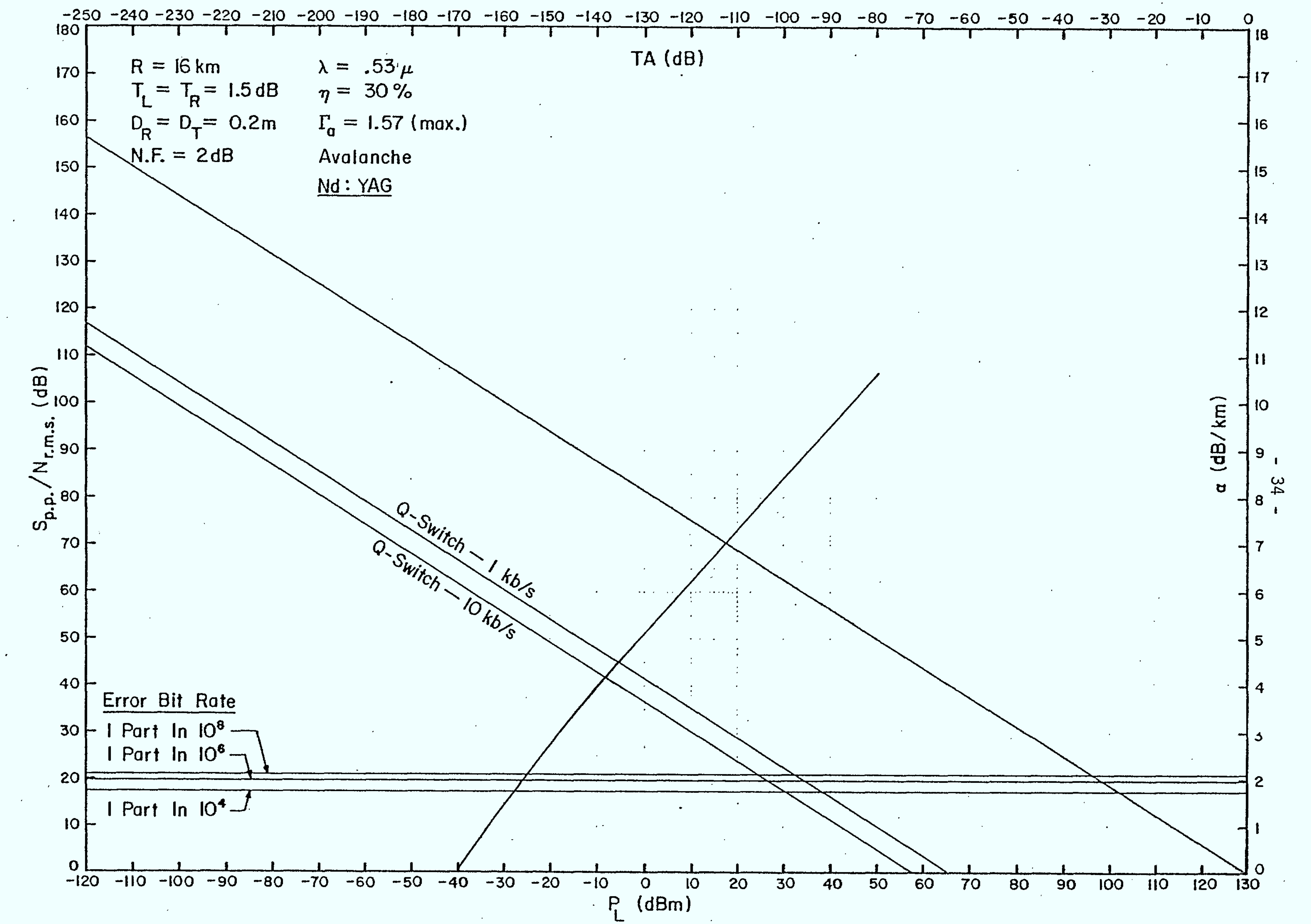

Fig. 15: Performance of a Q-switch second harmonics Nd-YAG laser communication system with envelope detection.

<u>CO_2 Laser Communication System</u>

Low Power CW Laser - Envelope Detection - 1kbit/100 kbit

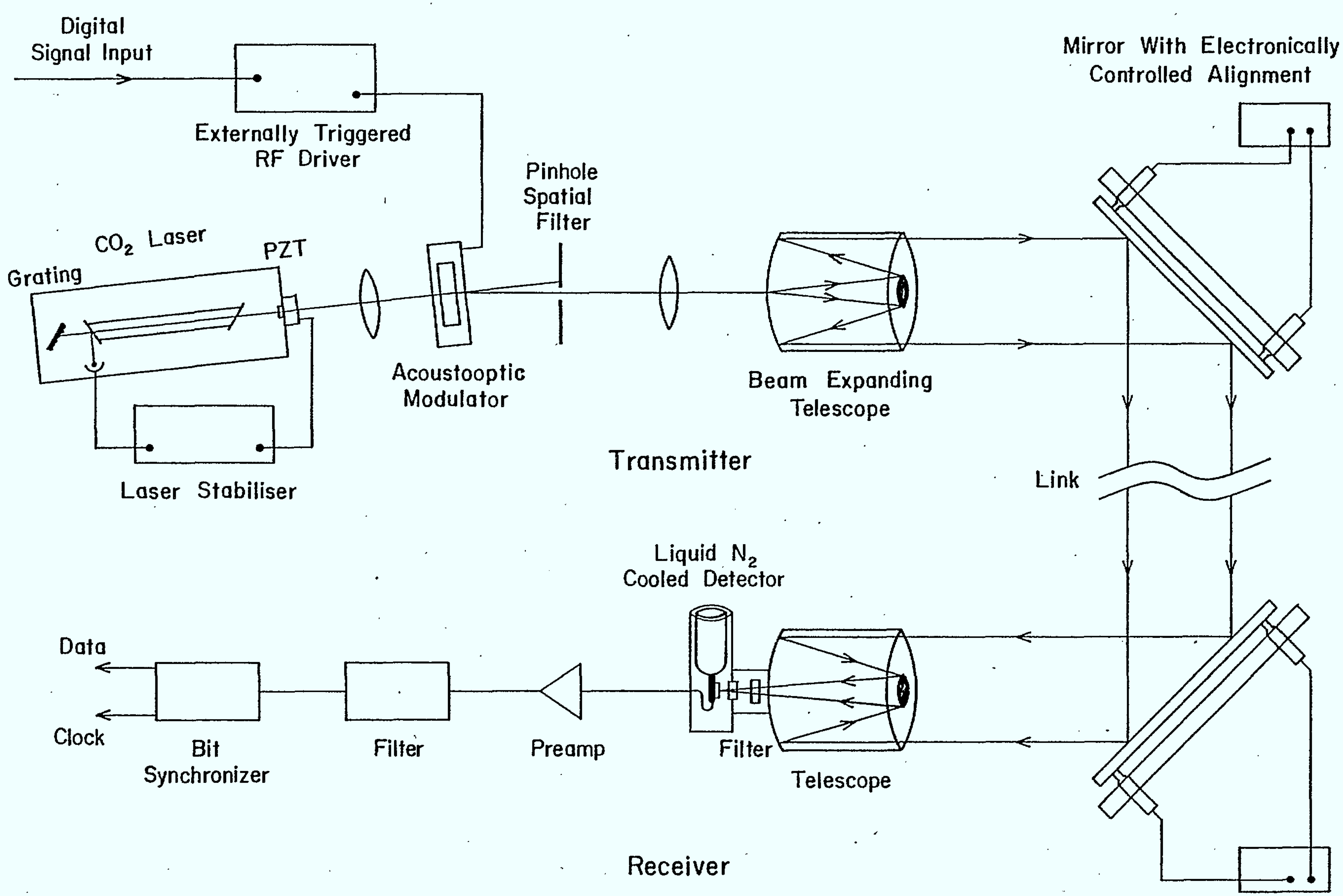

Fig. 16

NEP	2.95×10^{-12} W/Hz
Pre-amp Noise Figure	2 dB

Using these values, the computer generated optimized plots are given in Fig. 17 for the SNR as a function of P_L, for 100% modulation and a modulation index of Γ_a = .25 at 1 Kb/sec rate. An attenuation line for a CW laser output of 10 watts is also given.

It is seen that an error-bit rate of 1 part in 10^6 would demand attenuations of less than 4.7 dB/km and 4.3 dB/km for the 100% and Γa = .25 case respectively.

When the repetition rate is increased to 100 Kb/s, the results become as shown in Fig. 18. The maximum attenuations permissible for this higher rate system are 4 dB/km and 3.6 dB/km for the 100% and Γ_a = .25 cases respectively. For completeness, a 100 Mb/s system is shown and would permit a maximum attenuation of 2.7 dB/km for Γ_a = .25 (using an electrooptic modulator).

5.3.2 CO_2 Laser Operating in the Pulsed Mode

A CO_2 laser can be operated in a Q-switch or a pulsed mode. A typical pulse system is shown in Fig. 19. The system is similar to that shown in Fig. 16 except that the laser is a high power laser producing pulses with peak power of 2kW, pulse rate of 1 Kb/sec with pulse length up to 250μsec (e.g. Apollo Model 3000).

As discussed before, the required bandwidth for such a system would be in this case, about 4 KHz. Therefore, thanks to the long pulse length, very little wastage of the channel bandwidth occurs. With a Q-switch laser, this would not be true however as the pulse width would be typically 300 ns, and operation closer to that of the Nd:YAG laser would be achieved.

The results of the optimization is shown in Fig. 20.

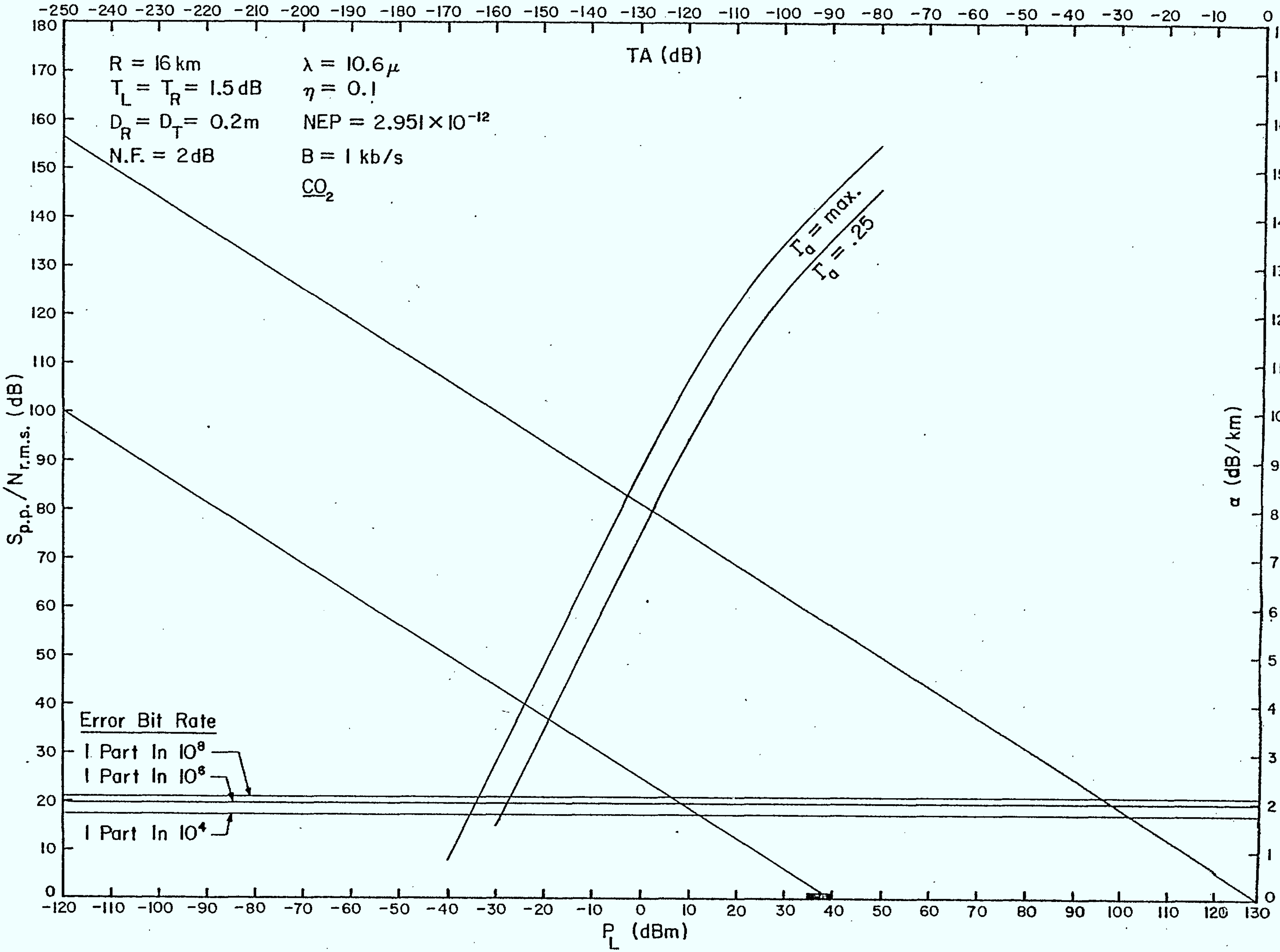

Fig. 17: Performance of a CO_2 laser communication system with external modulation and envelope detection at 1kb/s.

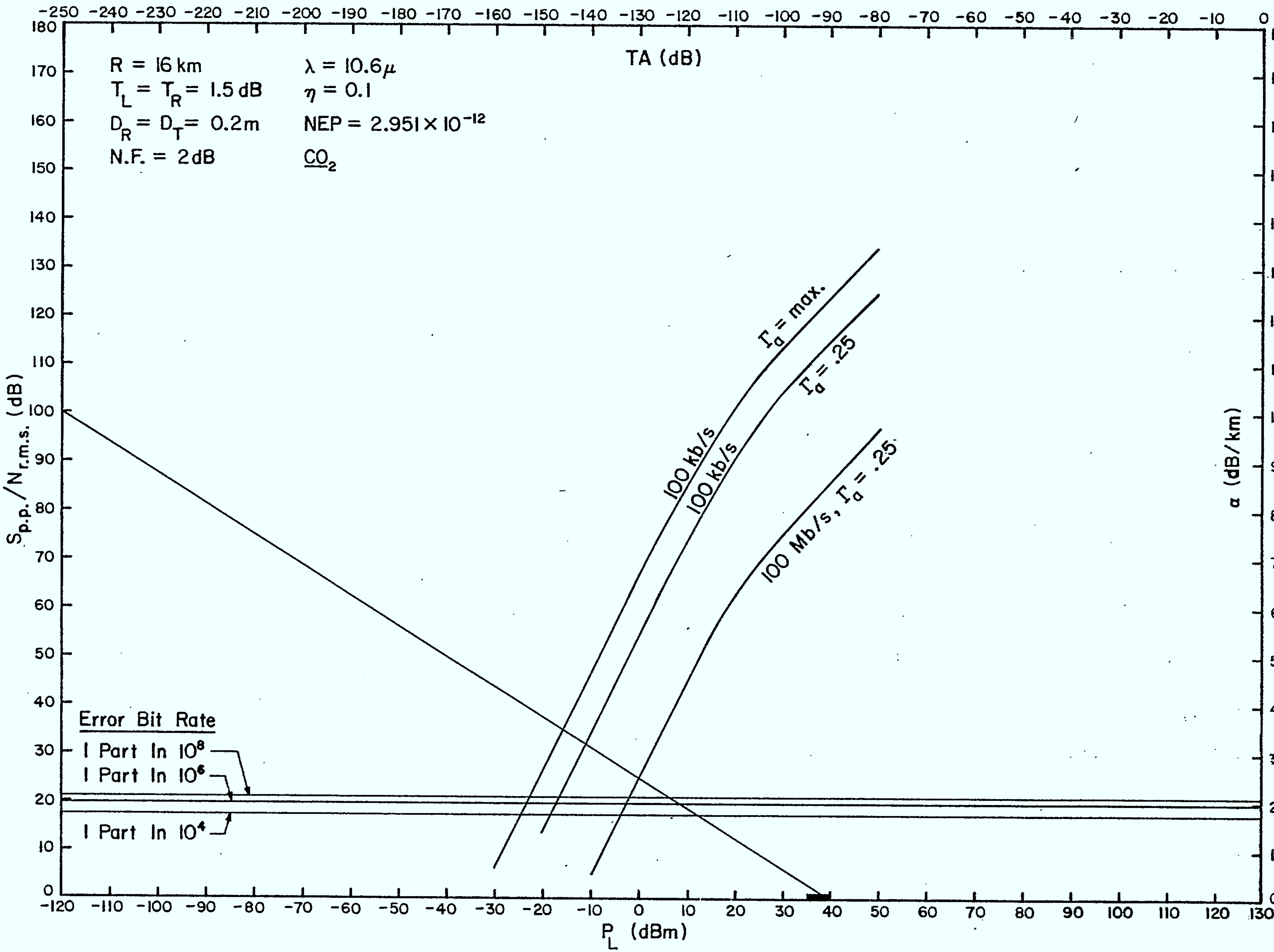

Fig. 18: Performance of a CO_2 laser communication system with external modulation and envelope detection at 100 kb/s and 100 Mb/s.

CO_2 Laser Communication System

High Power Pulsed Laser – Ikbit

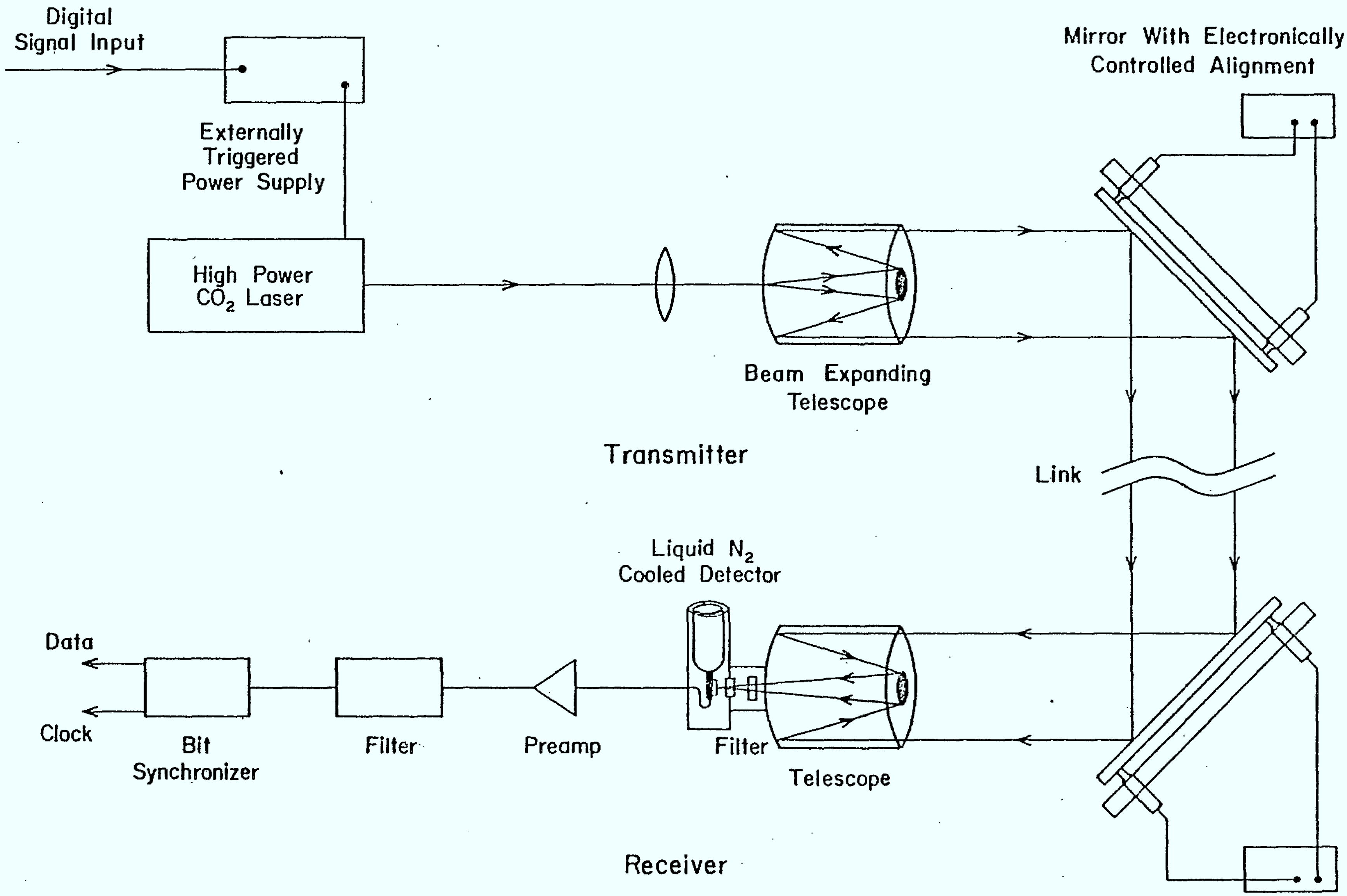

Fig. 19

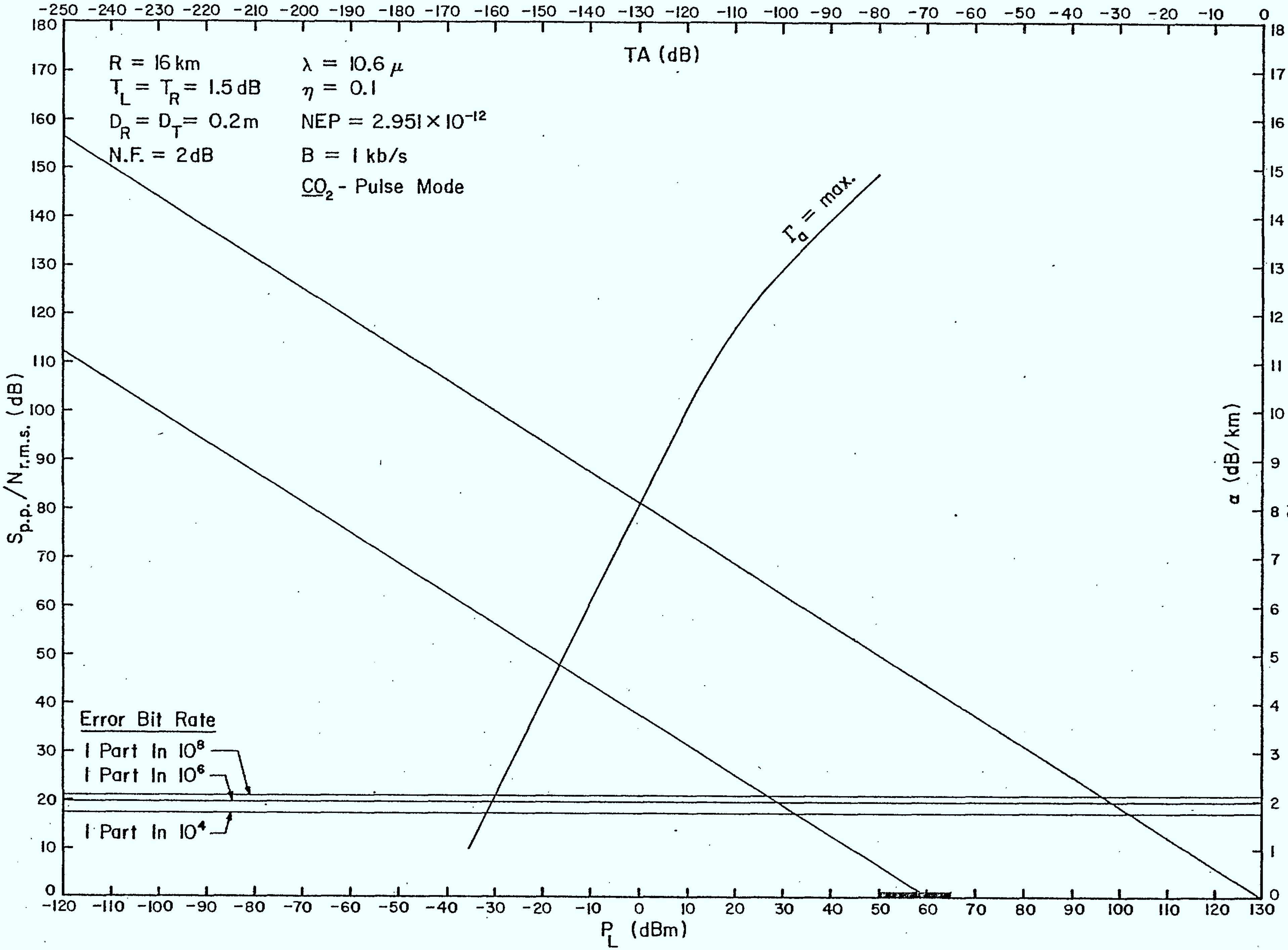

Fig. 20: Performance of a CO_2 laser communication system in pulsed discharge mode and envelope detection.

It is seen that for the 1 in 10^6 error bit rate, the maximum attenuation is now 5.7 dB/km. This is more than a full dB/km above the equivalent cw case. Such a laser cannot be operated at 100 Kbit/s however.

5.3.3 CO_2 Laser Operating in the TEA Mode

Extremely high powers can be obtained using this mode of operation. This however demands huge installations such as that required for fusion research. We shall consider a more modest TEA laser available from industry, for example the GENTEC DD300 series. Such a laser can produce up to 5 MW of peak power at repetition rate of up to 300 Hz. Typical pulse widths however are only 125 msec. The bandwidth requirement is therefore about 10 MHz. The system is shown in Fig. 21, which is essentially the same as that of Fig. 19 except that the laser is a TEA laser.

The optimization results for this case are given in Fig. 22. For the 1 in 10^6 error bit rate, the maximum attenuation permissible is 7 dB/km.

5.3.4 CO_2 Laser System Operating in the Heterodyne Mode

At the CO_2 laser wavelength, it is advantageous from the point of view of detection, to operate the system in the heterodyne mode as will be shown. In this mode of operation, the laser is well stabilized to ensure adequate coherence of the output. At the receiving end, detection is accomplished by heterodyning the received beam with a coherent local oscillator. This is shown in Fig. 23 for the case of a cw low power system with acoustooptic modulation as discussed before. The system is more complicated especially at the receiving end. The payoff is great however, as will be seen by the following examples.

a) CW Laser - External Modulation

Using the low power cw laser described in Sec. 5.3.1 but introducing heterodyne detection, we obtain the SNR's as shown in Fig. 24 for the 100%

CO_2 Laser Communication System

High Power TEA Laser – Envelope Detection – 0.3 kbit

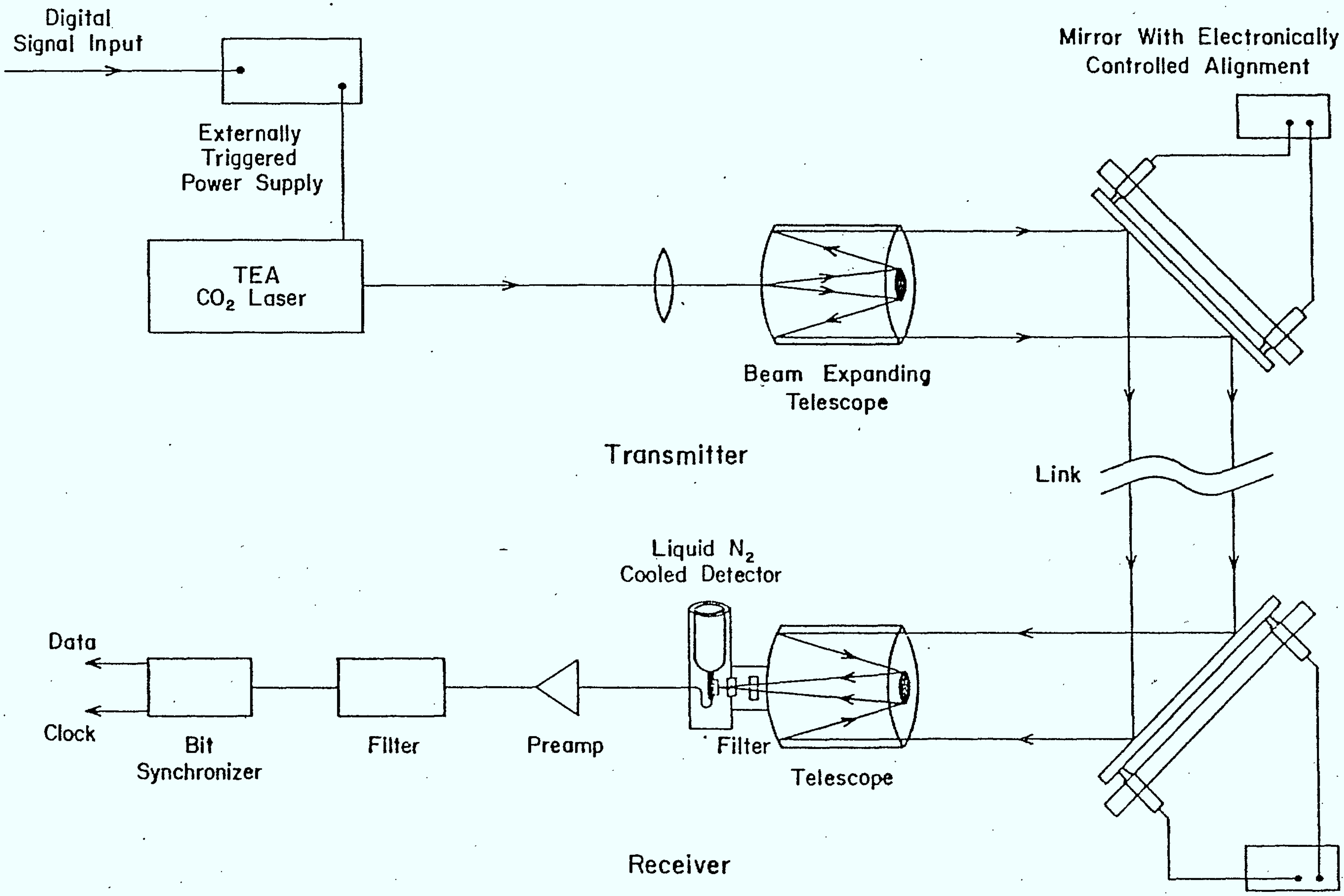

Fig. 21

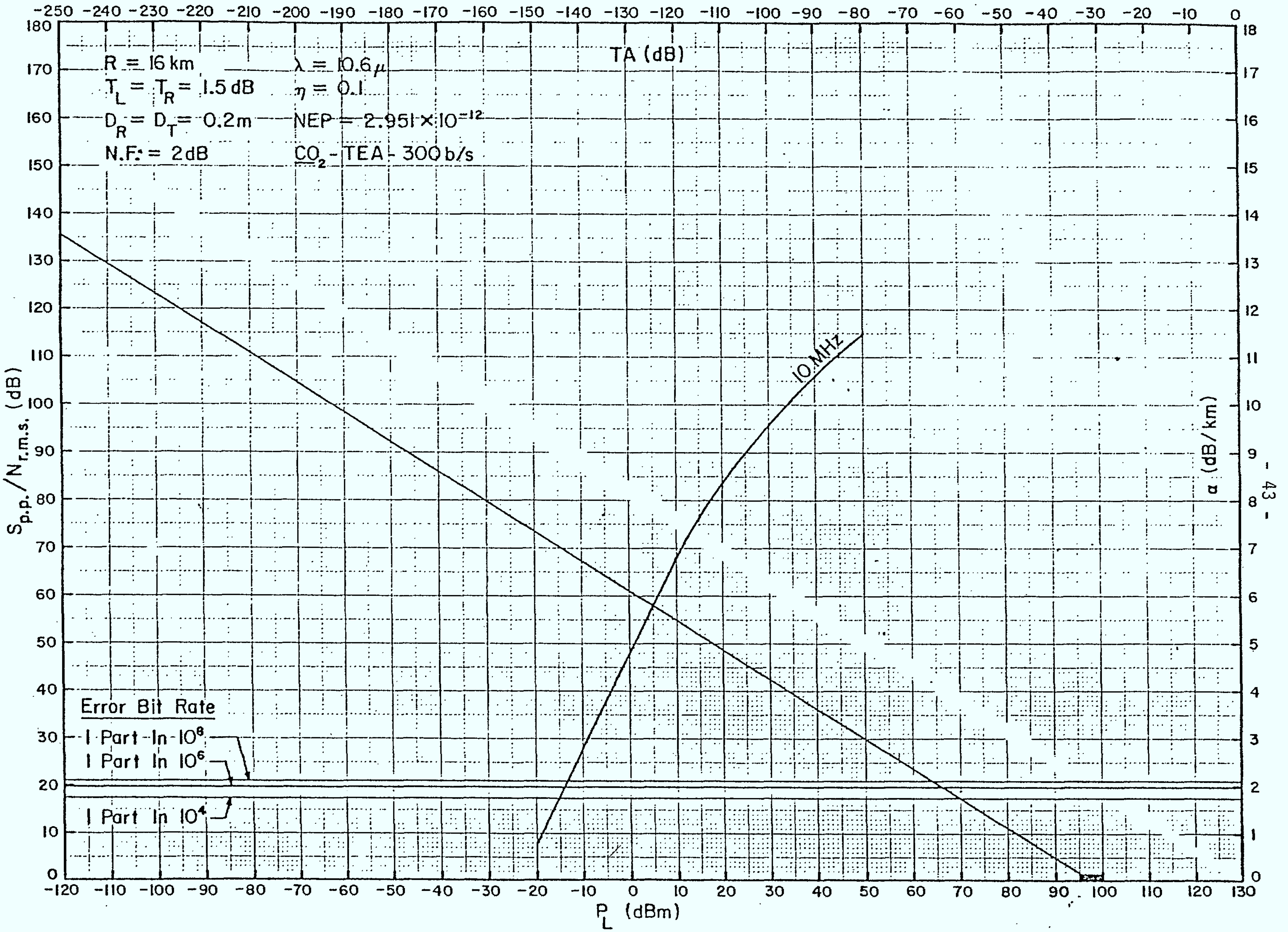

Fig. 22: Performance of a CO_2 laser communication system using the TEA mode and envelope detection.

CO_2 Laser Communication System

Low Power CW Laser - Heterodyne Detection - 1kbit/100 kbit

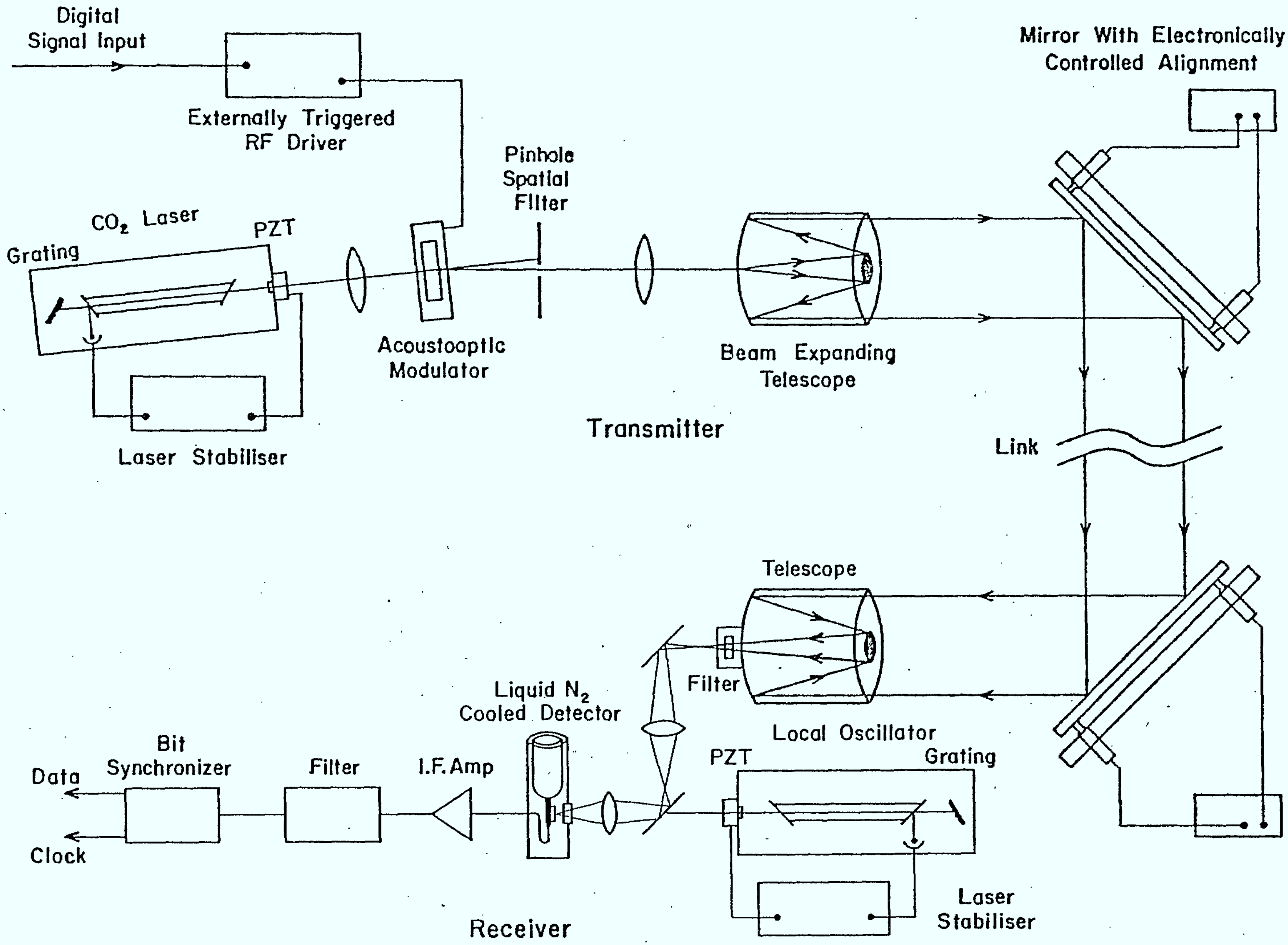

Fig. 23

- 44 -

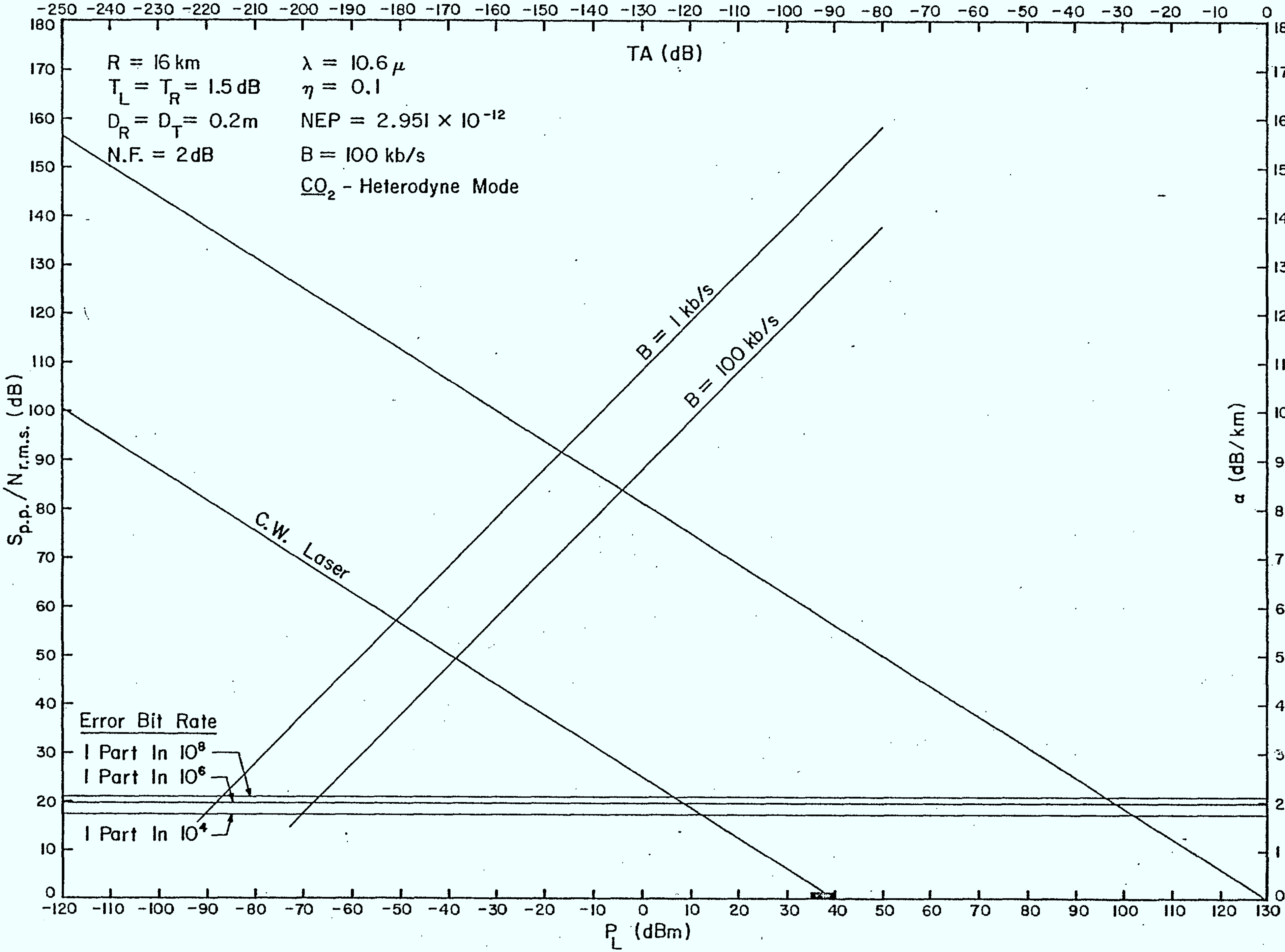

Fig. 24: Performance of a CO_2 laser communication system in the heterodyne receiving mode.

modulation case. It is seen that the permissible attenuations for 1 part in 10^6 is 8.1 dB/km and 6.8 dB/km for the 1 Kb/s and 100 Kb/s rates respectively. This compares to 4.7 dB/km and 4 dB/km for the equivalent envelope detection. This dramatic improvement is due to the fact that in heterodyne detection it is possible to get very close to shot noise limited operation.

b) Pulse Lasers

The high power lasers in the pulsed and TEA mode can also be operated in the heterodyne mode but by very elaborate and expensive systems. We shall report the results for these cases for completeness, understanding however, that the cost would be beyond the scope of this project. Fig. 25 shows the pertinent results for the pulsed and TEA laser described before but using heterodyne detection. The maximum attenuations for these cases, at the 1 per 10^6 error bit rate, are 8.8 dB/km and 0 dB/km respectively. It is interesting to note that the pulsed laser is doing almost as well as the more powerful (and expensive) TEA laser. This is because what is lost in power is offset in large measure by the much larger pulse width offered by the pulsed laser.

5.4 Summary of System Analysis

It might be of interest, for comparison purposes, to superimpose a number of performance curves on to one graph. This is done for the case of a repetition rate of 1 Kb/s for the three lasers discussed before, and is shown in Fig. 26. It should be recalled that these curves assume no attenuation through the atmosphere. For such cases, it is seen that the heterodyne CO_2 laser outperforms all others. This is followed in order by the He-Ne, Nd:YAG and finally the envelope CO_2 laser. Another way to look at it, is that for a given SNR, the absolute laser power requirement would be minimal for the case of the heterodyne CO_2 laser.

When atmospheric attenuation does come into play, however, the amount of available laser power becomes a major consideration in the final performance.

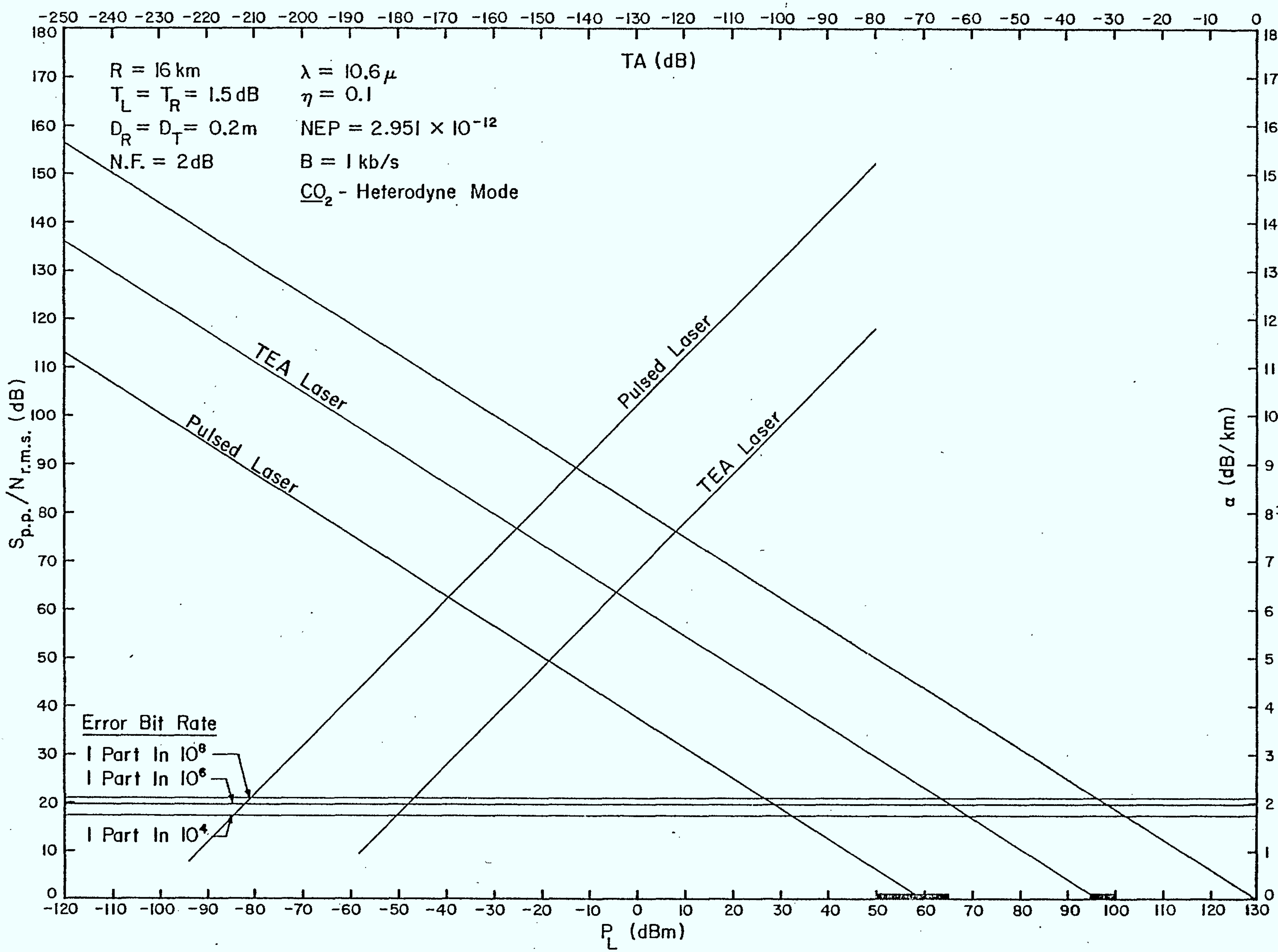

Fig. 25: Performance of a CO_2 laser communication system in a pulsed and TEA mode and heterodyne detection.

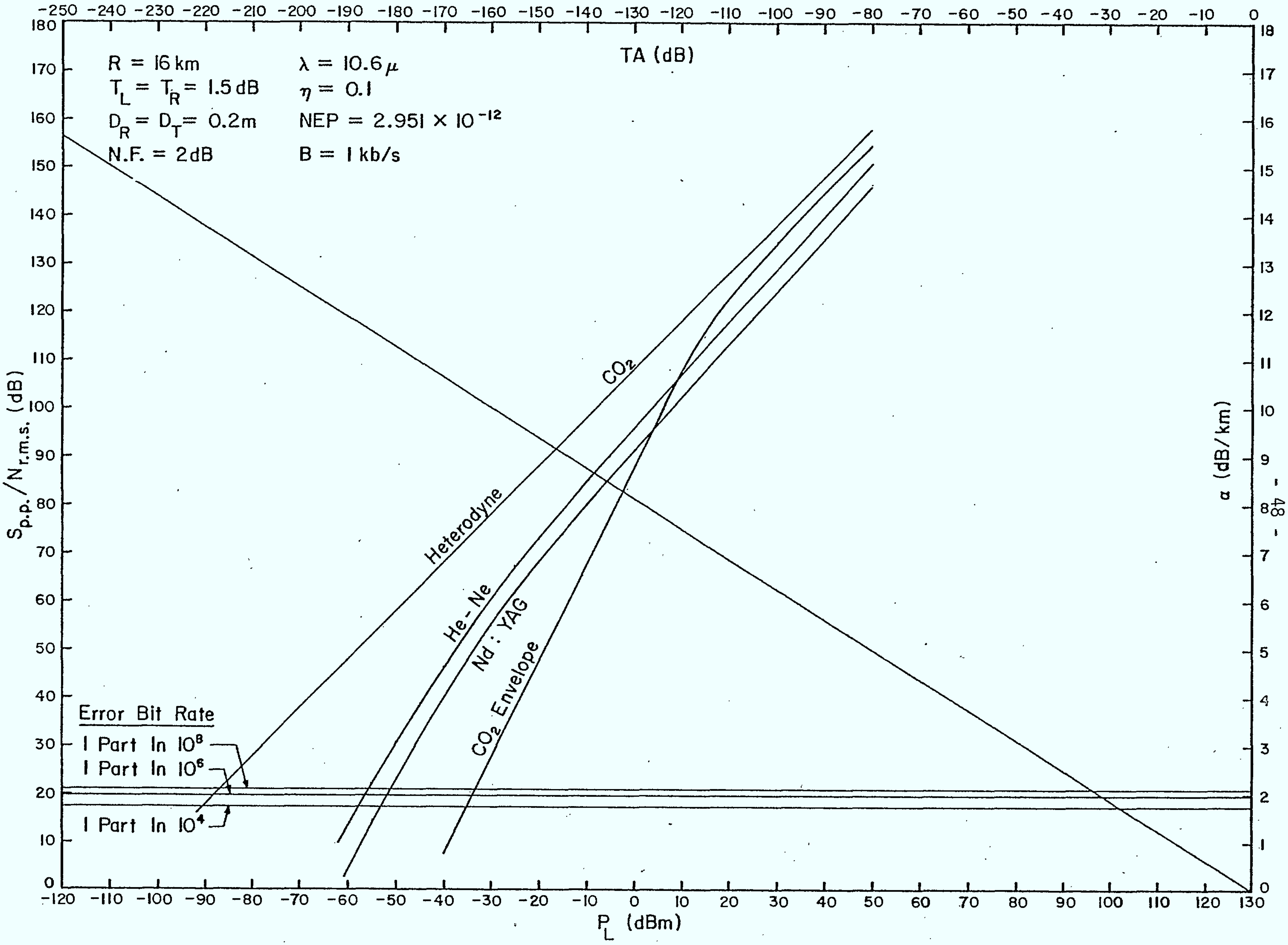

Fig. 26: Performance comparison of various laser communication systems.

As an example, although the He-Ne laser requires less power than the Nd:YAG laser system for equal performance, when weather attenuation increases the demand on laser power, the He-Ne laser system is quickly left behind. This is because a He-Ne laser is limited in maximum available power to about 100 mW whereas the Nd:YAG laser can supply power many orders of magnitude above this level. A summary of expected performances has been prepared for all cases discussed above and is given in Table I.

A perusal of this table indicates that, strictly in terms of performance alone, system 6 would permit highest weather attenuation, followed by systems 4, 2, 5, 8, 11 etc. It will be seen that considerations such a complexity and cost will reduce the choice considerably. In the last column is shown the estimated % of time the weather attenuation will be expected not to interfere with the performance of this particular system (for error bit rate less than 1 part in 10^6). This is taken for the region of Montreal from results given in Fig. 7. In the case of Nd:YAG laser a value somewhere between the CO_2 and the He-Ne case is assumed. A question mark is put beside these values to show that they are estimates only.

Laser Safety Considerations

When a laser is used in a communication system, it is important to ensure that the beam intensity at the receiving location is small enough not to cause a health hazard to the eye. As a guideline, we shall use the American National Standards Institute report #ANSI Z 136.1-1980 governing the safe use of lasers. It is found that the maximum permissible exposure for intra-beam viewing depends on a number of parameters such as the wavelength, pulse width, etc.

An analysis of each system shows that the only cases of concern are for systems 3, 4, 5, 6, 11, 12, 15, 16 which include the large CO_2 and

Nd:YAG pulse lasers. For these cases, the transmission should always be adjusted so that, after atmospheric attenuation, the received power is below the maximum permissible level. All the systems treated here using cw operation and external modulation have been found to be safe.

As a general comment, we can add that in general, the CO_2 laser is considerably safer than lower wavelength lasers. This is because the fluid that fill the eye - or vitreous humour, is opaque to the CO_2 laser radiation and hence stops it from reaching the retina. As a result, the maximum permissible exposure for intra-beam viewing of the CO_2 laser is at least two orders of magnitude larger than that for the other lasers. Consequently, the military requirements are shifting, in many cases, from Nd:YAG laser radars to CO_2 laser radars.

TABLE I

System	Laser	λ(μm)	PL	Mode of Operation	Detector	Demod. Tech.	Bit-Rate Kb/s	Maximum Attenuation for 1 in 10^6 dB/km	% Time Under This Attenuation
1	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Envelope	1	4.7	96.7
2	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Heterodyne	1	8.1	98.7
3	CO_2	10.6	1 kW	Pulsed	Hg:Cd:Te	Envelope	1	5.7	97.5
4	CO_2	10.6	1 kW	Pulsed	Hg:Cd:Te	Heterodyne	1	8.8	99.1
5	CO_2	10.6	5 MW	TEA	Hg:Cd:Te	Envelope	.3	7.	98.9
6	CO_2	10.6	5 MW	TEA	Hg:Cd:Te	Heterodyne	.3	9.	99.7
7	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Envelope	100	4.	96
8	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Heterodyne	100	6.8	98
9	CO_2	10.6	10W	C.W. (Γ_a=.25)	Hg:Cd:Te	Envelope	100(Mb/s)	2.7	93.6
10	Nd:YAG	1.06	6 W	C.W.	Avalanche	Envelope	1.	5.6	97.2?
11	Nd:YAG	1.06	12kW	Q-Switch	Avalanche	Envelope	1.	6.	98.4?
12	Nd:YAG	1.06	2 kW	Q-Switch	Avalanche	Envelope	10	5.6	97.2?
13	Nd:YAG	1.06	6 W	C.W.	Avalanche	Envelope	100	4.9	96.5?
14	Nd:YAG	1.06	6.W	C.W.	Avalanche	Envelope	100 (Mb/s)	3.5	94. ?
15	Nd:YAG	5.3	5kW	Q-Switch	Avalanche	Envelope	1	5.8	98.3?
16	Nd:YAG	5.3	1kW	Q-Switch	Avalanche	Envelope	10	5.3	97. ?
17	He-Ne	.63	4mW	C.W.	Avalanche	Envelope	1	3.9	94.4
18	He-Ne	.63	4mW	C.W.	Avalanche	Envelope	100	3.1	81.
19	He-Ne	.63	4mW	C.W. (Electrooptic)	Avalanche	Envelope	100 (Mb/s)	1.8	70.

6.0 PRICING ESTIMATES AND ANALYSIS

For the pricing estimate a number of assumptions were made; namely:

1. Price is F.O.B. (MPBT).
2. The detector is a liquid nitrogen cooled Hg:Cd:Te detector.
3. Both transmitter and receiver are placed in a typical lab environment, with technical attendance at both places. Therefore no weather protection is provided.
4. Receiver station is accessible to normal deliveries (e.g. liquid nitrogen).
5. No automatic acquisition is provided.
6. No automatic tracking is provided although remote controlled mirror alignment will be possible.
7. No installation cost at CRC is provided.
8. The material cost is subject to change by the manufacturer.

The estimated pricing is given in Table II.

When the prices are considered, it is seen that the He-Ne system is by far the cheapest, offering a two-way link for $147,000. The performance is however quite limited. System 4 and 6 have not been priced as they are technically very complicated and expensive and well beyond the budget of the initial phases of the program. Systems 9, 14 and 19 are only modestly more expensive than the others and require electrooptic modulation. The bit-rate however is well above the requirements of this project.

The most cost effective systems for reasonable performance appear to be systems 1, 7, 10, 11, 13. Finally, by far, the best upgraded performances are systems 2 and 8.

<u>TABLE II</u>

System	Laser	m	PL	Mode of Operation	Detector	Demod. Tech.	Bit-Rate Kb/s	Remark	Estimated Prices $ In Thousands
1	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Envelope	1	One-Way Link	150
2	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Heterodyne	1	One-Way Link	197
3	CO_2	10.6	1 kW	Pulsed	Hg:Cd:Te	Envelope	1	One-Way Link	195
4	CO_2	10.6	1 kW	Pulsed	Hg:Cd:Te	Heterodyne	1	-	-
5	CO_2	10.6	5 MW	TEA	Hg:Cd:Te	Envelope	.3	One-Way Link	213
6	CO_2	10.6	5 MW	TEA	Hg:Cd:Te	Heterodyne	.3	-	-
7	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Envelope	100	One-Way Link	164
8	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Heterodyne	100	One-Way Link	198
9	CO_2	10.6	10W	C.W.	Hg:Cd:Te	Envelope	100(Mb/s)	-	-
10	Nd:YAG	1.06	6 W	C.W.	Avalanche	Envelope	1.	One-Way Link	145
11	Nd:YAG	1.06	12kW	Q-Switch	Avalanche	Envelope	1.	One-Way Link	148
12	Nd:YAG	1.06	2 kW	Q-Switch	Avalanche	Envelope	10	One-Way Link	148
13	Nd:YAG	1.06	6 W	C.W.	Avalanche	Envelope	100	One-Way Link	145
14	Nd:YAG	1.06	6 W	C.W.	Avalanche	Envelope	100 (Mb/s)	-	-
15	Nd:YAG	5.3	5 kW	Q-Switch	Avalanche	Envelope	1	One-Way Link	167
16	Nd:YAG	5.3	1 kW	Q-Switch	Avalanche	Envelope	10	One-Way Link	155
17	He-Ne	.63	4 mW	C.W.	Avalanche	Envelope	1	Two-Way Link	147
18	He-Ne	.63	4 mW	C.W.	Avalanche	Envelope	100	Two-Way Link	147
19	He-Ne	.63	4 mW	C.W. (Electrooptic)	Avalanche	Envelope	100 (Mb/s	-	-

7.0 SUMMARY OF ADVANTAGES AND DISADVANTAGES

Before getting to the recommendations for the system to be used it might be useful to highlight the main advantages and disadvantages of communications systems based on the three lasers we have considered.

CO_2 Laser System - 100 kb/s (cw Envelope)

Advantages

- Good Haze Penetration
- Is In The Mainstream Of Laser Communication R & D
- Can Be Expanded To Heterodyne Reception
- Can Be Expanded To Q-Switching (1kW)
- Can Be Expanded To TEA Operation 10MW
- Can Be Expanded To High Repetition Rates (> 100 Mb/s)
- Can Be Expanded To Mode Locked Operation (Waveguide)
- Can Be Expanded To Send T.V. Pictures
- Very Efficient Laser ~ 20%
- Can Have A Large Canadian-Made Content
- Can Be Used For Over-The-Horizon R & D Experiments
- Relatively Eye-Safe

Disadvantages

- Usually Requires Cooled Detectors
- Optics Is Less Standard

Nd - YAG Laser System - 100kb/s (C.W. Envelope 1.06)

Advantages

- Is In The Mainstream Of Laser Communication R & D
- Can Be Expanded to Q-Switch 10kW Operation
- Can Be Expanded to Mode-Locked 1Gb/s Operation

- Can Be Expanded To The Green Wavelength (.53 μm
- Can Be Used For Submarine Communication R & D
- Can Be Used For Over The Horizon R & D

Disadvantages

- Low Efficiency
- Eye Safety Requirements More Stringent
- High Power Systems Usually More Expensive Than CO_2 System
- Less Canadian-Made Content

Helium Neon Laser System - 100Kb/s

Advantages

- Low Cost
- Can Be Expanded to 100 Mb/s With Small Increase In Cost
- As A Visible Laser - Ease Of Acquisition
- As A Visible Laser - Good For Training
- As A Visible Laser - Good For Demonstration
- Can Be Expanded To Transmit a Good T.V. Picture
- Can Be Expanded To Use Mode Locking Techniques
- Eye Safe Because Of Very Low Power Involved

Disadvantages

- Max. Power ~100mW
- Low Efficiency
- Could Not Perform Over The Horizon Work
- Is Not On The Mainstream Of Laser Communication R & D

8.0 RECOMMENDATION OF FINAL SYSTEM

A meeting was held at CRC on March 9, 1982 at which the advantages and disadvantages of the various systems discussed in this report were examined. A decision was taken for the selection of the system that would make most sense in terms of the criteria listed before and within the cost constraint of the program. The system recommended was system 7. This is the low power CO_2 laser system externally modulated and envelope detected. This would be updated eventually into a coherent system with heterodyne detection which was described here as system 8. The preliminary design of this system is given in the next section.

9.0 PRELIMINARY DESIGN AND PREDICTED PERFORMANCE FOR RECOMMENDED SYSTEM

The recommended system is as shown in Fig. 27. The CO_2 laser is assumed to be a 10W single mode, sealed CW laser giving out a high quality reliable TEM_{00} mode. A grating is used for the selection of the operating line. A stabilizer is incorporated to stabilize the laser operation to the line centre.

The external modulator is an acoustooptic modulator using a germanium single crystal as the active element. The modulation bandwidth is 2 MHz, well above our requirement of 100 KHz. It will therefore permit expansion into higher bit rates. It requires, however, water cooling for its operation. Diffraction efficiency of 70% is possible. Contrast ratio close to 1000:1 could be expected. The desirable detector would be a cooled Hg:Cd:Te detector of the SAT type. This would allow best performance. It however requires liquid nitrogen cooling or an equivalent cooling system. Other alternative detectors are possible but at a severe cost in performance. One such detector is a new type of room temperature Hg:Cd:Te detector developed in Poland, its NEP is close to 4 orders of magnitude higher than a cooled detector. Finally, room temperature pyroelectric detectors could be used but at the cost of a still lower performance.

Performance Evaluation

Having chosen the main components of the system, it is now possible to calculate a performance evaluation of the system. We have computed the predicted optimum S/N (p.t.p. to r.m.s.) in dB's as a function of atmospheric attenuation. The results are given in Fig. 28 and 29 for the 1 Kb/s and 100 Kb/s case respectively. For each of these, three detectors are assumed. The best result is for a typical SAT cooled detector (NEP = 3×10^{-12} W/ Hz). The next best system is that for the room temperature MCT detector. Finally the poorest result is obtained from a pyroelectric type of detector.

It is seen that acceptable atmospheric attenuations for 1 Kb/s at

CO_2 Laser Communication System

Low Power CW Laser – Envelope Detection – 1 kbit/100 kbit

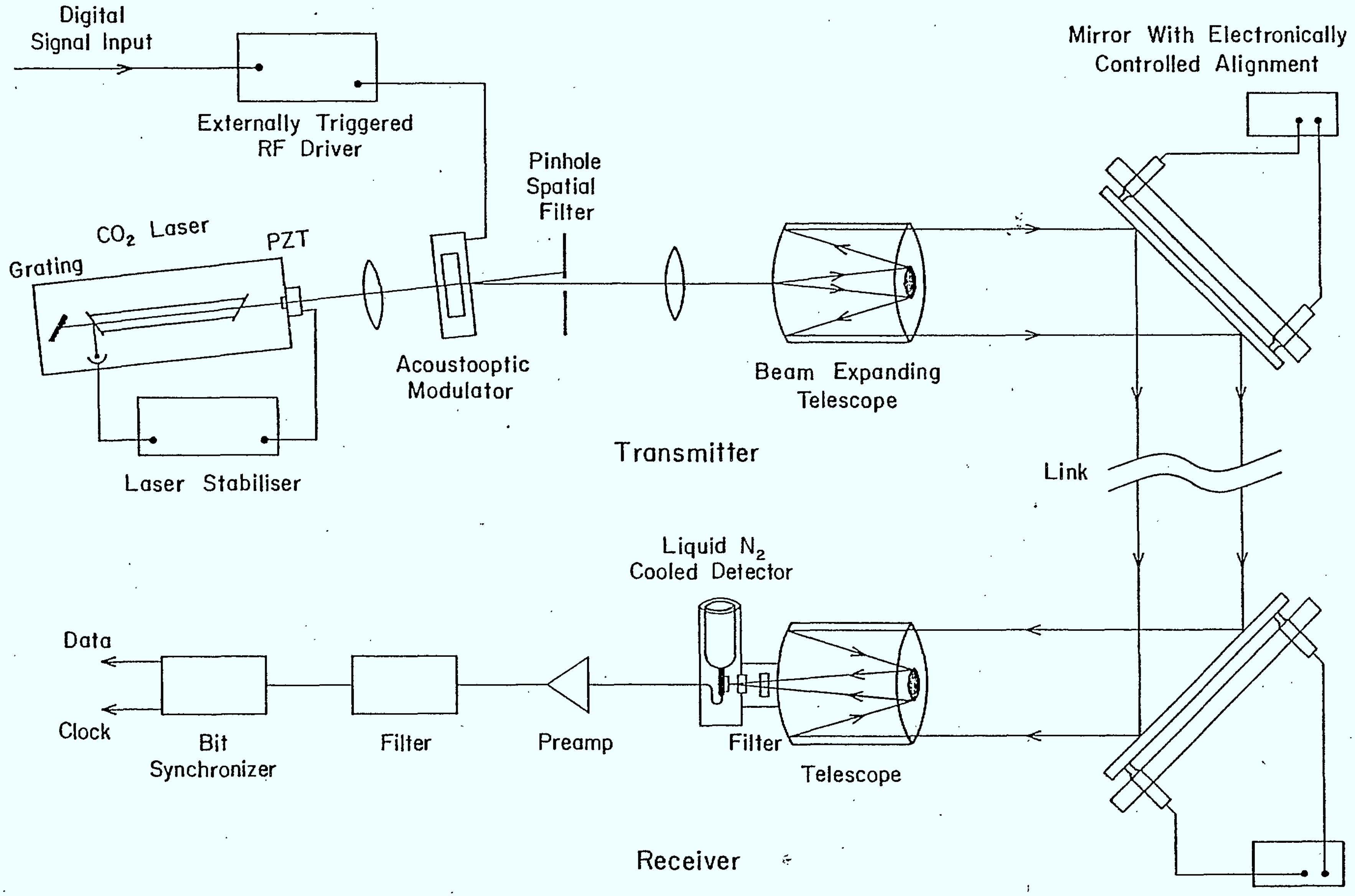

Fig. 27

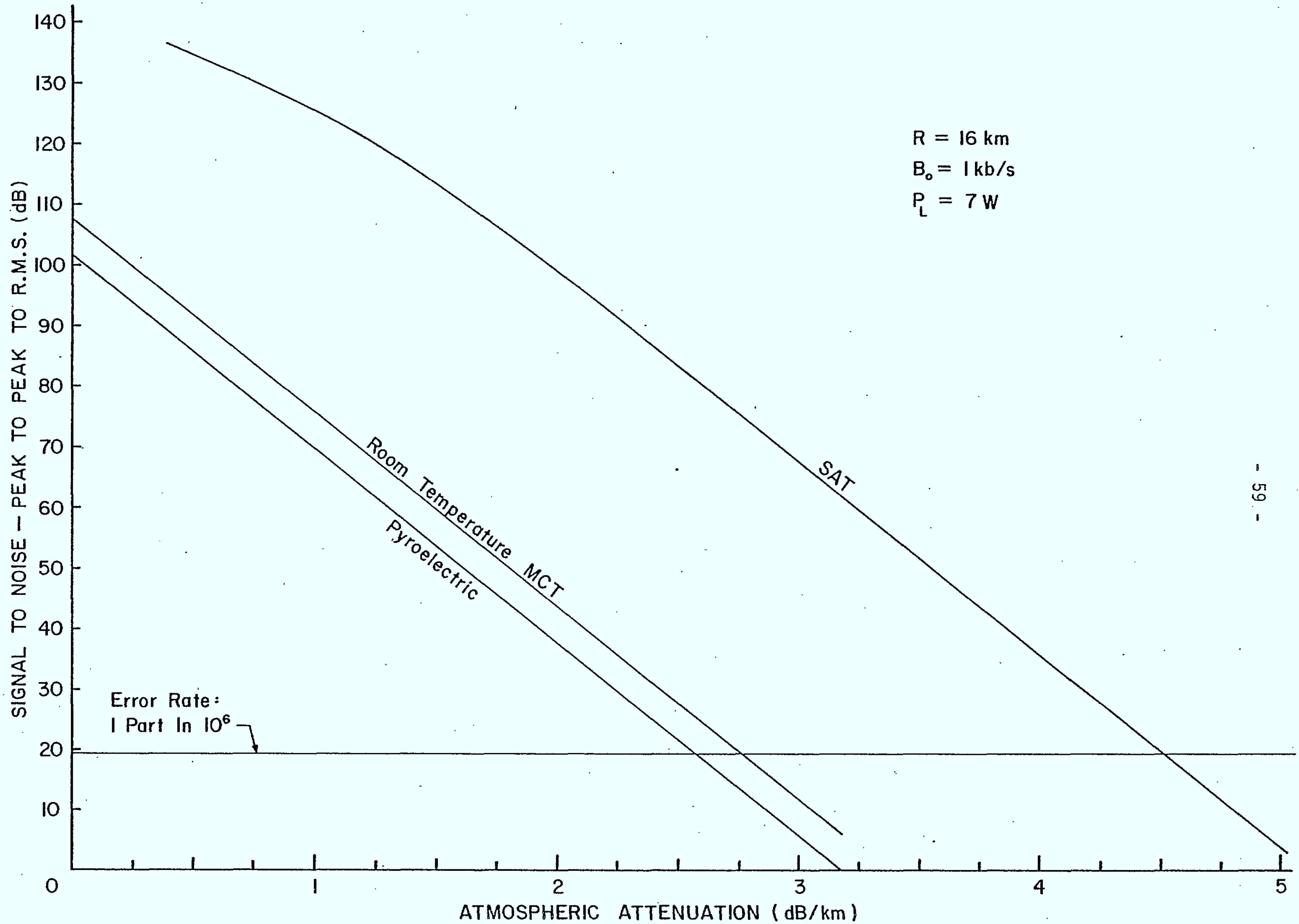

Fig. 28: Theoretical performance for the recommended CO_2 laser communication system (1kb/s).

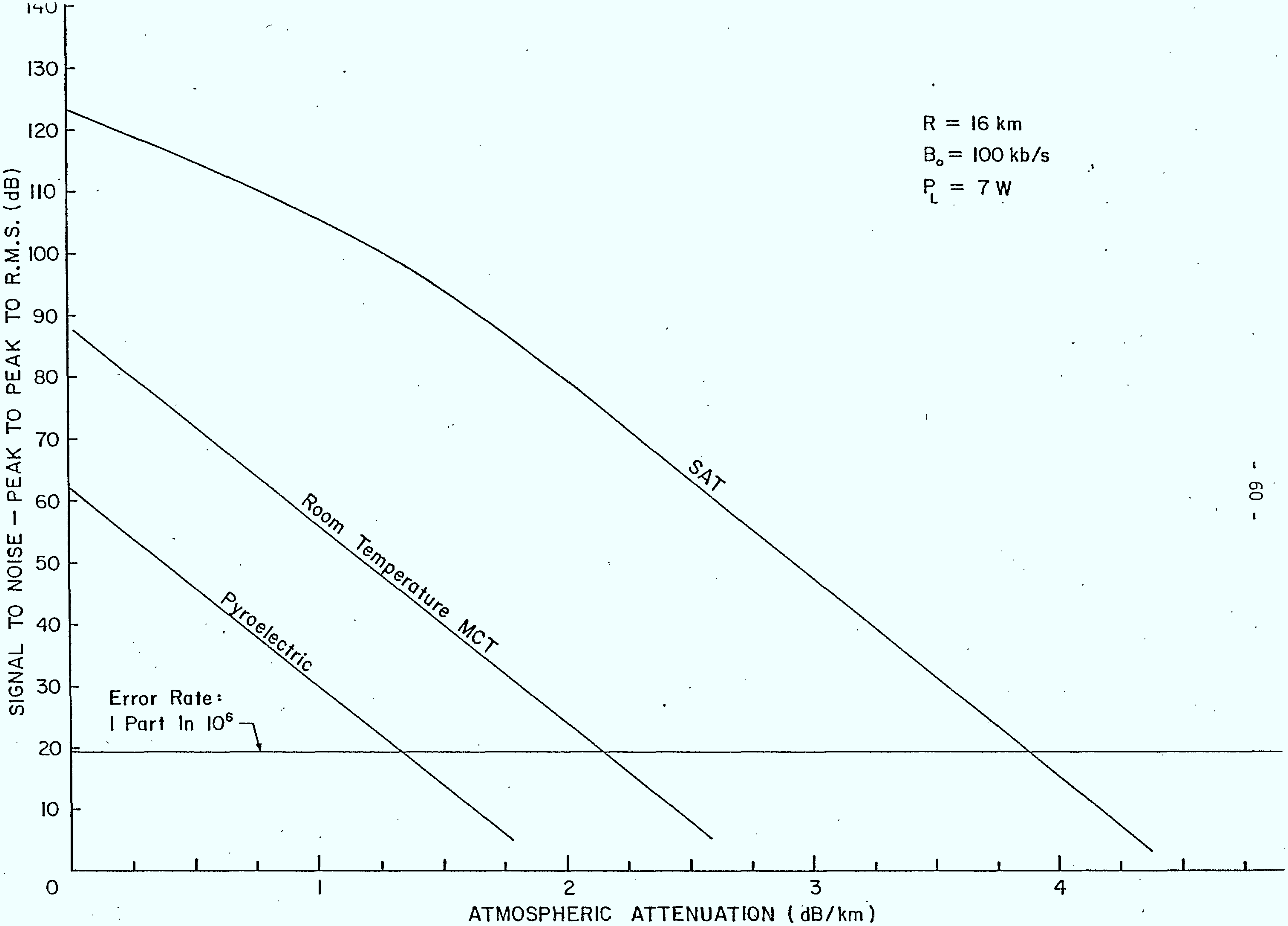

Fig. 29: Theoretical performance for the recommended CO_2 laser communication system (100kb/s).

error bit rate of 1 part in 10^6 are 4.5, 2.75 and 2.6 dB/km for the three detectors respectively. For the 100 Kb/s case, the respective attenuation are 3.9, 2.15 and 1.35 dB/km.

Long Lead Items

The major long lead items in this system include the laser system, the acoustooptic modulator and the detector.

10.0 LASER COMMUNICATION FACILITY REQUIREMENTS

Since this will be an experimental link it is strongly recommended that both transmitter and receiver stations be manned during the experiments - at least during the initial «debugging» period.

It was assumed, in the technical and the cost analyses, that both stations had a reasonable lab type of environment. By this we mean one in which the temperature does not vary widely, the platform on which the systems would be installed to be rigid, vibrations to be small, etc. Any departure from this would require an improvement in the systems which entails more sophistication and cost. A few examples will be given:

Platform Stability

Since no automatic tracking is anticipated in the initial phase of the experiment, then the angular stability of the transmitter beam has to be maintained to within close tolerances. This can be calculated approximately by the following consideration. The beam spot size at the receiving end would be adjusted to be about 1m in diameter. To keep the signal within 3 dB of the nominal power level, requires a linear displacement of the beam of less than 0.4m. Over a distance of 16 km, this is equivalent to an angular stability of about 25 μ radian. Our experience has shown that, for a link of about 1 km in length, it was possible to maintain adequate stability but only after a few days of repeated re-alignment until the system finally settled. After this initial period, we had to re-optimize every week or so. The accuracy requirements for the present link being 16 times more demanding, emphasizes the desirability of having the stations manned. Less stringent requirements could be secured by widening the beam but at a cost of a decrease in total performance of the system (higher susceptibility to atmospheric attenuation).

It should also be stressed that if additional mirrors are required to fold the beam, the angular stability requirement for each mirror has to be increased correspondingly so that the total angular movement of the system stays within specifications.

Accessibility to the Sites

An important consideration is the accessibility to both transmitter and receiver sites. Apart from occasional alignment requirements, it is assumed that liquid nitrogen would be available at the receiving station to cool the detector. If this is not the case, then a special joule Thomson cooler would have to be used with added complexity and expense. Alternatives would be to use a new type of room temperature Hg:Cd:Te detector or pyroelectric detector but at a cost to the total performance of the system as discussed in Section 9.

Miscellaneous Requirement

A number of facilities normally found in a lab environment is assumed. These include water for cooling, power, scopes, voltmeters, etc.

Possible Alternatives

In case there are major obstacles to adequate facilities and/or stability criteria at the receiving station, an alternative solution could be envisaged, namely installing a retro-reflector at the receiving station location. The actual receiving would thus be made at the transmitter station. The advantage of course would be that all equipment including transmitter and receiver would be placed at the same location. Also, small angular drifts at the retro-reflector location would be of no major concern. The price to be paid for this, however, is that the effective range of the link would now be 32 km reducing the availability of the link to the limited number of days when atmospheric attenuation is very low. Also the flexibility of a 2-station link would be lost.

For example, opportunities for experience with automatic acquisition, tracking, etc. that could be incorporated at a later date, would be lost. This mode of operation is therefore not recommended except as a last resort.

Another alternative that could be contemplated if the present receiving station is not easily accessible, is to locate an alternative site where an adequate building already exists and which is easily accessed by road.

11.0 OVER THE HORIZON COMMUNICATION

True «over the horizon» (OTH) communication refers to communication, via scattering from atmospheric aerosols or clouds, between two points for which no direct line of sight exists due to the curvature of the earth. This not only includes communication between two ground based sites but also between a satellite and an earth station located beyond the satellite's optical horizon. This latter application of OTH propagation has important implications for Canada in relation to the establishment of communications links between geostationary satellites and bases located in the far north. In this regard, Felstead[5] has recently carried out some preliminary calculations using the base at Alert N.W.T. as a typical example. The results show that propagation via the scattering channel has the potential to extend communication from a proposed Canadian military satellite located at 109° W longitude to Alert which lies ~ 3.5° beyond the satellite's geometrical line of sight.

In view of the potential importance of OTH propagation and in keeping with the primary objective of the program, to provide a learning experience in laser satellite communications, it would be desirable to include in the program experiments involving propagation through the scattering channel as well as those relying on direct line of sight. Unfortunately, such experiments will not be possible with the low power CO_2 laser system selected (in part due to budgetary constraints) for the initial experimental link. However, in anticipation of future upgrading of the system, some preliminary (and very approximate) calculations have been carried out to illustrate the signal levels that can be anticipated in experiments over the 16 km link involving propagation via aerosol scattering. Received power levels have been calculated for two systems, one based on a frequency-doubled Nd:YAG laser operating at 0.53μ, the other on a CO_2 laser with a wavelength of 10.6μ.

11.1 Geometry for Optical Scattering Propagation Experiment

The geometry for an optical scattering propagation experiment over the proposed 16 km CRC link is shown in Fig. 30.

Since a direct line of sight does actually exist between the transmitter and receiver sites, care must be exercised in selecting the transmitter elevation angle to insure that the signal detected at the receiver is truly the result of aerosol scattering. In this regard, it must be remembered that the intensity profile of the transmitted laser beam contains an infinite series of concentric secondary diffraction maxima (of steadily diminishing intensity) extending outward from the central intensity maximum. This intensity profile can be roughly approximated by the Fraunhofer diffraction pattern for a circular aperture

$$I(y) = \left[\frac{2\,J_1(y)}{y}\right]^2 I(o) \qquad (1)$$

where J_1 is the Bessel function and $y = \frac{2\pi a}{\lambda}\sin\theta$ with λ being the wavelength, a the aperture radius and θ the angle between the central beam axis and the line joining the center of the aperture and a given point in the observation plane. The intensity profile represented by Eq. 1 is plotted in Fig. 31 in order to illustrate the way in which the intensities of the secondary maxima fall off with increasing distance from the central beam axis. The variable x introduced in Fig. 31 denotes the distance from the beam axis in terms of the $1/e^2$ intensity radius (which is commonly used to denote the radius of a laser beam). For $x \gtrsim 2$, the intensity of the maxima falls off approximately as $1/x^3$. Now, since the received power for the aerosol scattering signal at 0.53μ is anticipated to be $\sim 10^{-12}$ of the transmitted power (based on the results

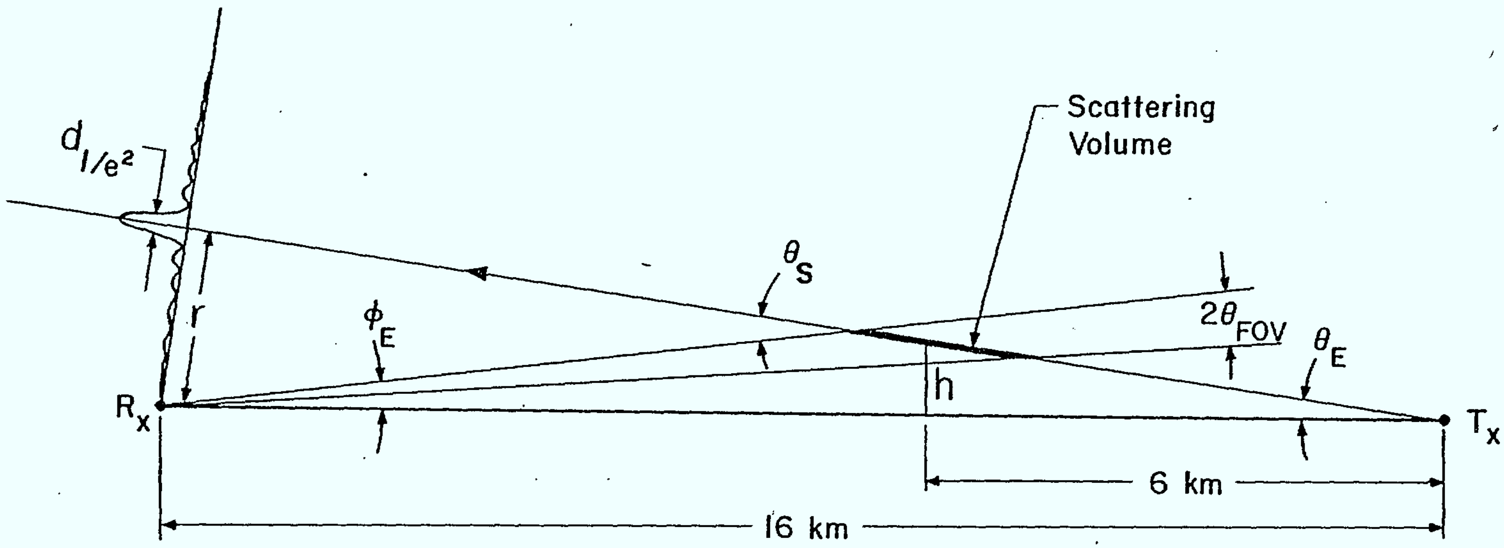

Fig. 30: Geometry for optical scattering propagation experiment over proposed 16km CRC link.

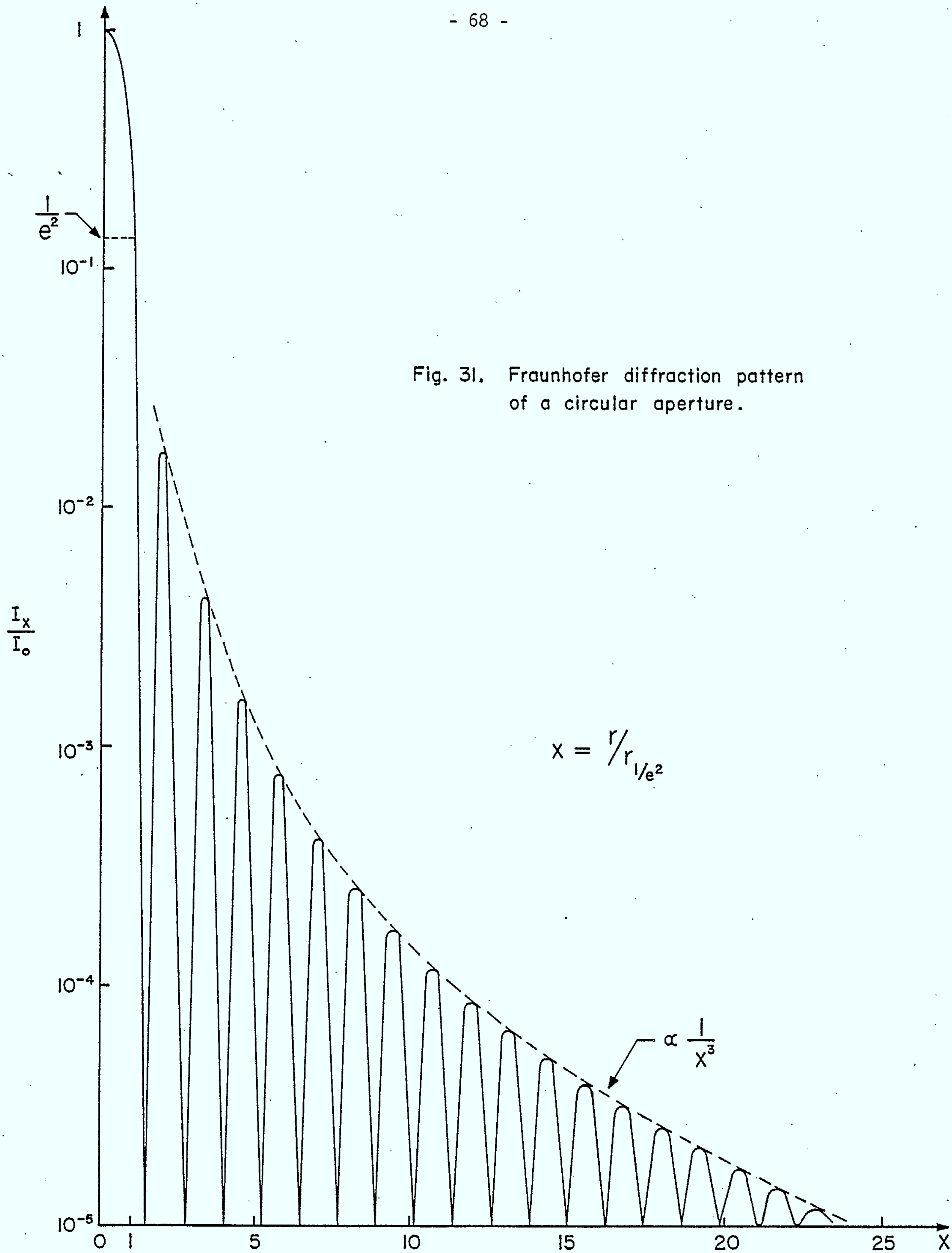

Fig. 31. Fraunhofer diffraction pattern of a circular aperture.

of experiments at the U.S. Naval Ocean Systems Center[6]), the transmitter elevation angle should be chosen so that the distance r indicated in Fig. 30 corresponds to a point in the beam profile where the intensity of the secondary maxima has fallen to $\sim 10^{-12}$ of the maximum on-axis intensity. This requires a value of $r \sim 5.2 \times 10^{3}\ r_{1/e^2}$ or, for a laser beam with a diameter of 1m at the receiver end of the link, $r \sim 2.6$ km which implies an elevation angle θ_E of $\sim 9°$ for a 16 km link. Additional discrimination against the «direct» signal can be provided by inserting a spatial filter in front of the detector (since the direct beam will be imaged at a different point in the focal plane of the receiving telescope than the radiation emanating from the scattering volume).

The scattering volume is defined by the intersection of the laser beam and the cone of half-angle θ_{FOV} representing the receiver's field of view. For the calculations that follow, the receiver elevation angle ϕ_E was rather arbitrarily chosen to be $\sim 6°$ which results in the scattering volume being located ~10 km from the receiver at a height h of ~1 km. With this arrangement, the scattering angle ($\theta_S = \phi_E + \theta_E$) is $\sim 15°$. This is still considered to be within the small angle scattering range in which a number of approximations can be made which greatly simplify the calculations of the received power.

11.2 Sample Calculations for Laser Communication Via Aerosol Scattering

Calculations of the received power, based on the single scatter model of Mooradian et al[6], have been carried out for two possible laser systems operating over the proposed 16 km CRC link according to the geometry described above. From these results and calculations of the noise contribution due to the background sky radiance, signal-to-noise ratios and bit error rates have also been determined.

From Ref. 6, the ratio of power received to power transmitted in the small angle, single scatter approximation is given by

$$\frac{P_R}{P_T} \approx \frac{\omega_o \, \alpha \, A \, e^{-\alpha d}}{r} \int_{\theta_S - 2\theta_{FOV}}^{\theta_S} p(\theta) d\theta \qquad (2)$$

where ω_0 is the single scatter albedo (defined as the ratio of scattering to extinction), α is the extinction coefficient, A is the area of the receiving telescope aperture, $p(\theta)$ is the normalized scalar phase function, d is the distance along the laser beam from the transmitter to the point of closest approach to the receiver and r, θ_S and θ_{FOV} are as shown in Fig. 30.

Now, for a cloud of particles characterized by a particle radius distribution function n(a) where a is the particle radius and $\int n(a)da = N$, the total number of particles per unit volume, $\omega_0 \, p(\theta)$ for small angle scattering is given by (6)

$$\omega_0 \, p(\theta) = \frac{\int_0^\infty dx |S(\theta,x)|^2 \, n(x/k)}{4\pi \, \mathrm{Re} \int_0^\infty dx \, S(0,x) \, n(x/k)} \qquad (3)$$

where $x = 2\pi a/\lambda$, $S(\theta,x)$ is the complex single scattering amplitude for scattering angle θ and Re denotes the real part. Since the phase function for small angle scattering is dominated by Fraunhofer diffraction contributions from particles large compared to the wavelength (ie: $x \gg 1$), $S(\theta,x)$ can be approximated by

$$S(\theta,x) \approx \frac{2 \, J_1(x \sin\theta)}{x \sin\theta} \, S(0,x) \qquad (4)$$

Analytical expressions for $|S(0,x)|^2$ and Re $S(0,x)$ for nonabsorbing particles with (real) dielectric constant m are given in Ref. 6.

$$|S(0,x)|^2 = \frac{x^4}{4}\left[1 - \exp(-2|\frac{m^2-1}{m^2+2}|x)\right]^2 \quad (5)$$

$$\text{Re } S(0,x) = \frac{x^2}{2}\{1 - \exp\left[-(\tfrac{4}{3})^{1/4}|\frac{m^2-1}{m^2+2}|^{1/2}x\right]\}^4 \quad (6)$$

For the purposes of the present calculations, the particles are assumed to be liquid water with a dielectric constant of 4/3. In addition, the particle size distribution is taken as the continental component of the maritime aerosol distribution given by Wells et al[7] (after Junge[8])

$$n(a) = C\, a^{-4} \exp(-h/_{h_c}) \quad (7)$$

where C is a constant, the details of which are unimportant for our purposes since it appears in both numerator and denominator in the expression for $\omega_o\, p(\theta)$ and therefore cancels out. h_c is a scale height factor which has a value (at a 1 km altitude) of 0.3 km for particles of radius 0.1μ to 1μ and -0.89 for particles >1μ.

The expression for n(a) above is strictly speaking not valid for a $\gtrsim$ 20μ since physically, particles larger than 20μ tend to settle out under the influence of gravity.

For the very approximate calculations carried out here, the integrals appearing in the expression for $\omega_o\, p(\theta)$ were evaluated graphically by plotting the integrands against x and estimating the area under the curves. In both the visible (λ = 0.53μ) and I.R. (λ = 10.6μ) cases the integration extended over values of a ranging from a ~ λ to a ~ 20μ. The resultant value for

$\omega_o\, p(\theta)$ was then assumed to be ~ constant over the $2\theta_{FOV}$ range of θ so that $p(\theta)$ could be taken outside the integral appearing in the expression for P_R/P_T.

The number of background (ie: noise) photons n_b detected per bit integration time T was calculated from the expression(9)

$$n_b = \frac{2\pi N_b\, T\eta\lambda WA \sin^2 \theta_{FOV}}{hc} \tag{8}$$

where N_b is the background sky radiance, η is the detector quantum efficiency, W is the optical bandwidth of the receiver, A is the area of the receiving telescope aperture, h is Planck's constant and c is the velocity of light.

11.3 Results

11.3.1 System 1

The characteristics of the first system considered are as follows:

Transmitter

Laser	Nd:YAG (frequency doubled)
λ	0.53μ
Peak Power, P_p	6 kW
Pulse Width, τ	100 ns
PRF	1 KHz

Receiver

Aperture Area, A	$\pi \times 10^{-2}$ m^2
θ_{FOV}	5 mr
η	0.15
Optical Bandwidth, W	10Å (1.1×10^{12} Hz)

The calculation of $\omega_o\ p(\theta)$ for $\theta = 15°$ yielded a value of ~ 0.3 and when this is substituted in the equation for P_R/P_T along with the values $\alpha = 0.1\ km^{-1}$ (visibility ≈ 40 km), r = 2.6 km and $d(=16\ \cos\theta_E) = 15.8$ km, one obtains

$$\frac{P_R}{P_T} \cong 7 \times 10^{-13} \qquad (9)$$

Therefore the number of signal photons detected per pulse n_s $(= P_R\eta\tau\lambda/hc)$ is

$$n_s = \frac{7 \times 10^{-13} P_p\eta\tau\lambda}{hc} = 105 \qquad (10)$$

The background sky radiance at 0.53μ is ~ 10^{-21} W/m^2.sr.Hz for night time operation and ~ 10^{-13} W/m^2.sr.Hz during the day(9). Substituting these values into the expression for n_b and assuming a digital system operating at one bit per laser pulse (ie: $T \sim 3\tau$), one obtains

$$\begin{aligned} n_b &\sim 6 \times 10^{-4} \quad \text{(night time)} \\ n_b &\sim 6 \times 10^{4} \quad \text{(day time)} \end{aligned} \qquad (11)$$

From a comparison of the day time value of n_b with n_s, it is clear that day time operation is impossible and therefore it will not be considered further. If a cooled photomultiplier is assumed for the detector, the dark count accumulated over time T can be neglected and the ratio $\mu = n_s/(n_b + n_d)$ defined in Ref. 9 becomes $\mu = n_s/n_b$, yielding

$$\mu \sim 1.7 \times 10^{5} \quad \text{(night)} \qquad (12)$$

From Fig. 8 of Ref. 9 (with $\beta = n_s$), the error probability P_e is vanishingly small ($<< 10^{-20}$). In order to get an idea of the permissible margin for error in the calculation of P_R/P_T, if n_s were an order of magnitude less than the value given above, μ would become ~ 1.7×10^4 yielding a still acceptable error probability of ~ 4×10^{-5}. In this connection, it is worth noting that the results of propagation measurements at a wavelength of 0.6328μ in the Montreal area [4] indicate that α is less than the assumed value of 0.1 km^{-1} approximately 20% of the time and less than 0.28 km^{-1} approximately 50% of the time. If the latter figure is used in the calculation of P_R/P_T, n_s is reduced by a factor of ~ 6 and consequently, acceptable error probabilities might be expected ~ 50% of the time.

In addition to the approximate nature of the calculation of P_R/P_T, a note of caution is in order concerning the value of the background sky radiance used in the calculation of n_b. The value of 10^{-21} W/m^2.sr.Hz is appropriate for a clear night time sky in the absence of moonlight. It can vary over a range of 4 - 5 orders of magnitude [10] depending on the phases of the moon, its position relative to the receiver field of view (even assuming it is not directly in the field of view) and cloud conditions. Consequently, it is anticipated that error probabilities will rise to unacceptable levels during certain stages of the lunar cycle (depending in part on prevailing cloud conditions).

11.3.2 System 2

Similar calculations were then carried out for a CO_2 laser system with the following characteristics:

Transmitter

Laser	Pulsed CO_2
λ	10.6μ

Peak Power, P_p	2 kW
Pulse Width, τ	250μs
PRF	300 Hz
<u>Receiver</u>	
Aperture Area, A	$\pi \times 10^{-2}$ m^2
θ_{FOV}	5 mr
η	0.1
Optical Bandwidth, W	4 kHz (Heterodyne detection)

The use of a receiver incorporating heterodyne detection (to reduce the optical bandwidth) was dictated by the magnitude of the background sky radiance at 10.6μ. For a receiver elevation angle of 6°, $N_b \sim 2.5 \times 10^{-12}$ W/m^2.sr.Hz[11] and is approximately the same for both night and day time operation since the background at 10.6μ is primarily due to the emission of radiation of the molecules of the atmosphere which is essentially blackbody in nature. As a result, the day to night variation is largely the result of the relatively small difference in the blackbody spectral radiance at the day and night time ambient air temperatures.

With heterodyne detection, the bandwidth W can be reduced to the spectral width of the transmitted pulse which is approximately given by $(\tau)^{-1} = 4$ kHz. Under these conditions and with a bit integration time $T \sim 3\tau$, the number of background photons detected is

$$n_b \sim 2 \times 10^2 \quad \text{(day or night)} \tag{13}$$

The calculation of $\omega_o\, p(\theta)$ for $\theta = 15°$ yielded a value of $\sim 1.7 \times 10^{-3}$ and, assuming $\alpha \sim 0.009$ km^{-1}, $P_R/P_T \sim 1.7 \times 10^{-15}$. Therefore, the number of signal photons detected $n_s \sim 4.4 \times 10^3$ and neglecting the detector dark noise, $\mu \sim 21.5$. Again, from Fig. 8 of Ref. 9 (with $\beta = n_s$), the error probability is vanishingly small and even if n_s was a factor of 40 less than the value obtained above, the error probability would only be $\sim 4 \times 10^{-5}$. It is interesting that, because of the relatively low extinction coefficient in the infrared, increasing α from the assumed value of 0.009 km^{-1} ($\alpha < 0.009$ km^{-1} only 10% of the time[4]) to 0.07 km^{-1} ($\alpha < 0.07$ km^{-1} approximately 50% of the time[4]) leads to a 3-fold increase in n_s.

It should be noted that the calculated value of $P_R(\sim 10^{-15} P_T)$ is three orders of magnitude less than the incident power level due to the secondary maxima of the «direct» beam, for the assumed transmitter elevation angle of 9°. Increasing the elevation angle will not significantly improve the situation owing to the relatively slow decrease in the intensity of the secondary maxima with increasing r and the fact that P_R will also decrease with increasing scattering angle. Rather, care will be required to insure adequate spatial filtering in the focal plane of the receiving telescope and to minimize stray light scattering from the telescope optics.

11.4 Conclusions to Over the Horizon Communication Experiments

The foregoing approximate calculations were undertaken to illustrate the signal levels and error probabilities that might be anticipated for experiments over the proposed 16 km CRC link involving propagation via the optical scattering channel.

The results indicate that acceptable error probabilities ($< 4 \times 10^{-5}$) can be anticipated for night time operation of a frequency-doubled Nd:YAG laser system ($\lambda = 0.53\mu$). With the exception of certain stages of the lunar cycle, the system availability is expected to be $\sim$ 50%.

For a pulsed CO_2 laser system ($\lambda = 10.6\mu$) with heterodyne detection, system availabilities > 50% are expected for both day and night time operation. However, it should be pointed out that such a system would be considerably more expensive than the doubled Nd:YAG laser system.

One further note of interest concerns the possibility of OTH communication via direct detection of the secondary diffraction maxima. This possibility arises due to the fact that, after grazing the surface of the earth, the transmitted beam will eventually (in the far field) re-establish a series of secondary maxima similar in character to those accompanying the initial transmitted beam. However, in order to check the feasibility of this communications channel, detailed calculations would have to be carried out to investigate the reconstruction of the secondary maxima as the beam propagates by the curved obstruction represented by the earth.

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