Kodaikanal Obs.Bull.(1991) 11, 105-112

Use of Lasers in Satellite to Earth Communication Link

S.Sundar Kumar Iyer, M.Mukunda Rao
Laser Communication Laboratory
Electrical Engineering Department
Indian Institute of Technology
Madras 600 036

Abstract

With the growing demand of communication requirement all over the world, there is no way out but to go in for higher carrier frequencies. A far sighted move will be to go in for laser communication links in areas like earth to satellite communications. This paper gives a simple model of such a link comparing the various lasers that may be used. It also suggests the use of 9.11 μm CO_2 laser as a strong candidate for such a link.

Key words: laser communication, lasers, atmospheric propagation.

Introduction

The interest in laser communication for satellite application as an alternative to microwave links stems from the fact that the frequency of operation of the laser system is four to five orders of magnitude higher than that of the microwave systems. This gives the former three main advantages over the later - greater bandwidth, smaller beam divergence angle and smaller antennas. This in the former leads to higher bit rate of transmission with lesser power loss and the use of smaller antennas in satellites (which is a crucial factor in satellite communication).

There are some typical hurdles related to lasers - like acquisition and tracking, availability of laser sources and detectors at desired wavelength of operation. Also for atmospheric optical link, the constraints due to atmospheric vagaries in terms of absorption and scattering have to be overcome by proper selection of laser system and optimisation of entire link. This paper analyses the communication link between earth and a geostationary satellite.

Laser Sources

The beam distortion, absorption and scattering in the medium are wavelength dependent. Hence, the study of medium characteristics and laser source and detector availability must precede the selection of possible wavelength of operation. The laser selection for a link is made after considering the power output, efficiency, weight, volume, ruggedness and reliability. The four possible candidates for satellite link and their respective characteristics are given in Table I (Katzman 1987; Gagliardi 1987).

Table I. Characteristics of principal candidate laser sources

Laser type	Operating wavelength	Efficiency	Characteristics
GaAlAS	$0.86\mu m$	5-10%	.small,rugged and compact .directly & easily modulated .easily combined into arrays .nanosecond pulsing .50,000 life hours, reliable
Nd:YAG	$1.06\mu m$	0.5-1%	-requires eleaborate modulation equipment -requires diode pumping -40,000 life hours
Nd:YAG (doubled)	$0.532\mu m$	0.5-1%	-frequency doubling losses efficiency
CO_2	$10.6\mu m$	10-15%	discharge tube with all problems of seals, cathodes, anodes .has lifetime problems as the carbon dioxide changes to CO .Operates in the infrared region,no good detectors .heterodyne/homodyne detection

Earth - geostationary satellite link model

In such a link, the laser beam passes through the whole of the earth's atmosphere. Less than one millionth of the total atmospheric mass lies above 100 km (Driscoll & Vaughan 1978) and we neglect its effect on the laser beam.

Atmospheric effects

A mathematical model of the power as the beam passes through a distance x is given by

(Ross 1966)

$$P_x = P_0 exp(-\alpha x) \tag{1}$$

where α is the extinction coefficient given by

$$\alpha = \sigma_m + \sigma_a + k_m + k_a \tag{2}$$

where σ and k represent the scattering and absorption coefficients respectively and the subscript m and a stand for molecule and aerosol respectively. Here, Raman scattering is neglected.

The values of $\sigma_m, \sigma_a, k_m, k_a$ at various altitudes have been experimentally found out and tabulated (Driscoll & Vaughan 1978). Using these tables we have calculated the approximate value of $\hat{\alpha}L$ where $\hat{\alpha}$ is the mean attenuation coefficient and $L = 100$ km for the atmosphere for different laser source wavelength. These values are tabulated in Table II. The various attenuation coefficients have been plotted as a function of altitude for the different wavelengths (Fig. 1).

Table II. Different attenuation coefficients for 100 km for the different wavelengths

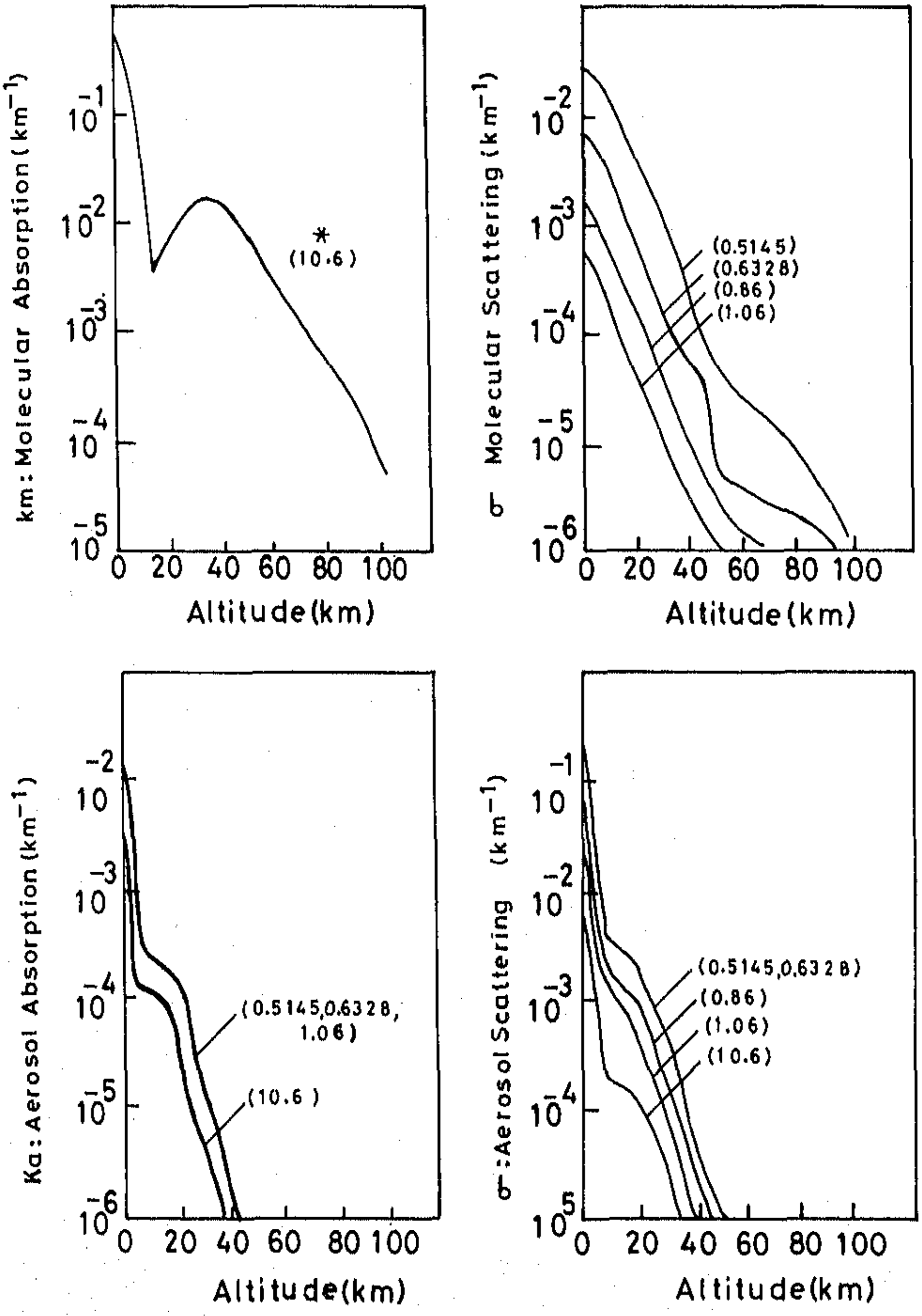
			clear sky		hazy sky	
λ (μ m)	molecular absorption $k_m L$	molecular scattering $\sigma_m L$	aerosol absorption $k_a L$	aerosol scattering $\sigma_a L$	aerosol absorption $k_a L$	aerosol scattering $\sigma_a L$
0.5145	0.0181	0.1300	0.0152	0.2515	0.0514	0.8522
0.6328	0.0472	0.0559	0.0138	0.2078	0.0469	0.7024
0.86	$< 10^{-6}$	0.0167	0.0155	0.1480	0.0524	0.5006
1.06	$< 10^{-6}$	0.0071	0.0164	0.1186	0.0555	0.4005
10.6	1.6931	$< 10^{-6}$	0.0114	0.0165	0.0169	0.0246

These attenuation coefficients are for tropical skies.

We assume the geostationary satellite subtends a zenith angle of 30^0 (worst case). The transmittivity τ_1 for such a case is given in Table III along with τ_∞ the transmittivity for 0^0 zenith angle.

Like aerosols, clouds and fog also attenuate a laser beam. The attenuation coefficient for visible light to around 6 μm increases very little. The minimum occurs around 10 μm.

The atmosphere also causes dispersion of laser beam leading to reduced bandwidth. For carrier wavelength 10 μm or below, available bandwidth is several GHz (Brookner 1970). In the present state of technology, the limiting factor is the bandwidth of the receiver used.



* The wavelength of light to which the graph corresponds to is given within the brackets.

Figure 1. Attenuating coefficients as a function of altitude.

Table III. Total attenuation coefficient and transmittivity (zenith angle 0^0 and 30^0) for the different wavelengths

$\lambda(\mu m)$	$\hat{\alpha}L$		$\tau_\infty = e^{-\hat{\alpha}L}$		$\tau_1 = (\tau_\infty)^{sec\theta}$	
	clear	hazy	clear	hazy	clear	hazy
0.532	0.4014	1.0222	0.6694	0.3598	0.6291	0.3072
0.86	0.1802	0.5697	0.8351	0.5657	0.8121	0.5180
1.06	1.1421	0.4632	0.8675	0.6293	0.8486	0.5858
10.06	1.7210	1.7345	0.1789	0.1765	0.1371	0.1350

Note: α for 0.532 μm is found by interpolation using preceding table.

Range equation

Using the Range equation (Karp 1988), we get

$$\tau_2 = \frac{P_r}{P_s} = \frac{A_s A_r}{\lambda^2 R^2} \tag{3}$$

where P_r is the power received, P_s is the power transmitted. The values of τ_2 for various λ_s tabulated in Table IV.

Table IV. The ratio of power received to power sent using the range equation for earth-geostationary satellite link

$\lambda(\mu m)$	τ_2
0.532	8.71×10^{-7}
0.86	3.33×10^{-7}
1.06	2.19×10^{-7}
10.6	2.19×10^{-9}

Note: 1. Here we have taken A_s, the source area and A_r, the receiver area as $\pi(0.15)^2/4$ (i.e. the diameters are 15 cm each).

2.The distance between source and detector, R, is the altitude of the geostationary satellite, i.e. 35,600 km.

Noise

The link under consideration can be made by limiting the background noise and by proper design of receiver. The background noise is also minimised by using optical filters centered around the carrier frequency.

Due to absence of scattered sunlight in space, the main source of background noise in the earth facing detector is earth shine - with other sources of noise being two orders lesser than earth shine. Also the link gets cutoff when the Sun is a direct background of the link (Pratt 1969).

Background noise is given by

$$P_R = \frac{d^2 A_r}{4R^2} W(\lambda)\Delta\lambda \tag{4}$$

where $W(\lambda)$ is the spectral radiant emittance. The background noise is tabulated in Table V using data in (Pratt 1969).

Table V. The spectral radiance emittance of earth and the background noise in a receiver in a geostationary satellite

$\lambda(\mu m)$	Spectral radiance emittance of earth W(λ) (Watt/sqcm-micron)	Background noise (Watt)
0.532	1.4×10^{-2}	2×10^{-5}
0.86	3.3×10^{-3}	4.7×10^{-6}
1.06	1.0×10^{-3}	1.43×10^{-6}
10.6	3.0×10^{-3}	4.3×10^{-6}

Note: The values of $W(\lambda)$ was found from Figure in (Pratt,1969) and the background noise was calculated using the equation (4). $A_r = \pi(\frac{0.15}{2})^2 m^2$.

SNR and power budget calculations

For direct detection (Karp 1988)

$$SNR = \frac{(\alpha P_r)^2}{(F_\alpha P_b)2B_b} \tag{5}$$

where F is the excess noise factor, B is the one-sided BW of detector output circuit.

For heterodyne detection (here used only for CO_2 laser)

$$SNR = \frac{2\alpha P_r}{[1 + 2\alpha N_{ob}]2B_n} \tag{6}$$

where N_{ob} is background noise power/Hz and B_n is the bandwidth of bandpass around IF.

For an SNR of 20 dB (for an acceptable BER), we calculate the power required to be transmitted. The results are given in Table VI.

Table VI. The power required by the different lasers to establish an earth geostationary communication link

$\lambda(\mu m)$	Power transmitted $P_T(W)$ clear	hazy
0.532	8.65	17.71
0.86	6.69	10.49
1.06	4.83	7.00
10.06	31.31	31.79

Discussion

The CO_2 laser requires to transmit higher power than other lasers, but its efficiency is also the highest (10% - 15%). The Nd: YAG laser has a low efficiency (0.5 % - 1%). The diodes have individually high efficiency, but the diode arrays' efficiency is low due to beam combining techniques in the present state of technology. So, roughly all require the same input power. Also, the power required by CO_2 laser is nearly same for clear and hazy weather conditions, unlike other lasers.

Table II reveals that for $\lambda = 10.6\mu m$, all factors of attenuation except molecular absorption are very small in comparison to that of the other wavelengths. The molecular absorption is highly wavelength specific and for $10.6\mu m$, it is due to CO_2 and H_2O molecules.

Lately, a 9.11 μm CO_2 laser has been developed by some companies using C^{13} isotope of Carbon. The abundance $C^{13}O_2$ in atmosphere is 0.0113 times that of $C^{12}O_2$ must be proportional to this. Using this fact and assuming (in the absence of available data) CO_2 and H_2O absorb 50% of energy each at 10.6 μm, we can estimate the molecular absorption for the 9.11 μm laser beam.

Thus, for $C^{13}O_2$ laser (9.11 μm), all parameters are calculated.

$\hat{\alpha}L = 0.8840$ (clear weather); 0.8976 (hazy conditions)

$\tau_\infty = 0.4131$ (clear weather); 0.4076 (hazy conditions)

$\tau_1 = 0.3603$ (clear weather); 0.3548 (hazy conditions)

$\tau_2 = 2.97 \times 10^{-9}$

$P_b = 3.6 \times 10^{-6} W$

$P_s = 1.09 \times 10^{-8}$

$P_T = 10.19$ W (clear weather); 10.34 W(hazy conditions)

The CO_2 laser uses heterodyne detector necessitating a laser on board the satellite. With the advent of waveguide CO_2 lasers, the lasers have become rugged and have longer life time. The power required (few hundred watts) can be generated by solar panels. Cryogenically cooled $HgCdTe$ detectors are nowadays being replaced by a very effective radiatively cooled detectors.

In spite of drawbacks regarding detectors with respect to other lasers, the 9.11 $\mu m CO_2$ laser is preferred due to its higher efficiency, high optical power generation capability and less variation in link performance due to weather conditions. The latest pulsed mode operation of CO_2 laser helps in high bit rate pulse modulations like PPM. Also, infra red lasers are least harmful to life form which becomes relevant as the discussed link is through the atmosphere.

Conclusion

Efficient communication link is feasible using $C^{13}O_2$ lasers. Suitable modulation scheme like PPM is to be used to extract the best performance in the link. At IIT-M, the design for PCM to PPM and vice versa has been developed. This helps the link to be compatible with the existing PCM communication links.

Before practical realisation, other aspects like acquisition and tracking of satellite which for narrow beams are challenging engineering problems, are to be worked out.

Laser links are also possible for inter satellite communication and satellite to submarine communication. With the growing pressure of communication traffic, it is not very distant in future, when we will have such links in commercial operation.

References

Brookner, E. 1970, Atmospheric propagation and communication channel model for laser wavelength, IEEE transactions on communication technology, Vol.Com-8,No.4, 396.

Driscoll, W.G., and Vaughan, W. eds. 1978, Handbook of Optics, Optical Soc. Am., McGraw-Hill, 14-1 to 14-63.

Gagliardi, R.M. 1987, Satellite Communications, CBS publishers and distributors, 356.

Hinkely, E.,et al. Laser Monitoring of the Atmosphere, Springer -Verlag, p36.

Karp, S.,et al. 1988, Optical channels, Plenum Press, New York, 5-9, 14-26 and 55-79.

Katzman, M. 1987, Laer Satellite Communication, Prentice-Hall, 1-10 and 39-50.

Pratt, W,K. 1969, Laser Communication System, John Wiley & Sons, p111.

Ross, M. 1966, Laser Receivers, John Wiley & Sons, p281.