The Noises' Limits of the Laser Satellite Communication System

MARKETA SMEJKALOVA MAZALKOVA
Department of Communication and Information Systems
University of Defence
65 Kounicova, 612 00 Brno
CZECH REPUBLIC

Abstract: - Optical space communications is on the verge of being reality. The paper involves the introduction into laser satellite communication system. The paper includes briefly analysis, optimization, and design and system level development of signal transferring between satellites. Research opportunities in this area include development of laser beam acquisition, tracking and pointing techniques and algorithms, development of computer aided analysis link budget for the free space channel, systems engineering (analysis and design) of optical transmission development of high efficiency flight qualifiable solid-state lasers, fast fine-pointing mirrors high update-rate acquisition and tracking cameras and very low-noise high-quantum efficiency receiver. It is focused on the noises' limits of the optical communication system. The paper solves the problems with noises' limits by various ways. There are mentioned the optical energy output on an aperture's spread of optical detector and incoherent detection of optical carrier wave.

Key-Words: - Laser, satellite systems, laser communication, space channel, noise limits, optical communication, range loss, signal transfer loss, satellite communications.

1 Introduction

The optical space communications are a key building block for wide-area space data networks. A crosslink, or communication between two satellites, may be needed to solve certain requirements of satellite communication architecture. Laser communications offers the user number of unique advantages over radio frequency (RF) systems, including size, weight, power and integration ease on the spacecraft. Integration ease issues include compactness of terminals, elimination of complex frequency planning and authorization, and RF interference issues [1].

Laser cross-links will be enable the transfer of data between satellites at rates compatible with ground fiber networks. This is an exciting era for space laser communications. Not only is information transfer driving the requirements to higher data rates, but laser crosslink technology explosions, global development activity, and increased hardware/design maturity are all contributing to interest in space laser communication [2].

2 The laser satellite system

The optical communication systems become more and more attractive as the interest in high-capacity and long-distance space links grows. Advancer in laser communication system architectures and optical components technology make such high capacity links feasible. The laser communication equation (LCE) is a basic resort of LICS's (Laser Inter-satellite Communication System) analysis. Based on the background and receiver noise and the type of signal modulation which is to be detected, a required signal is generated. The ratio of received signal to required signal is the system link margin. Identifying these gains and losses requires intimate knowledge of the system design, including both the internal constraints and design choices and knowledge of the external factors, including range, data rate, and required signal criteria. These parameters are of single-way data transfer for three independent links – acquisition, tracking and data transfer (figure 1).

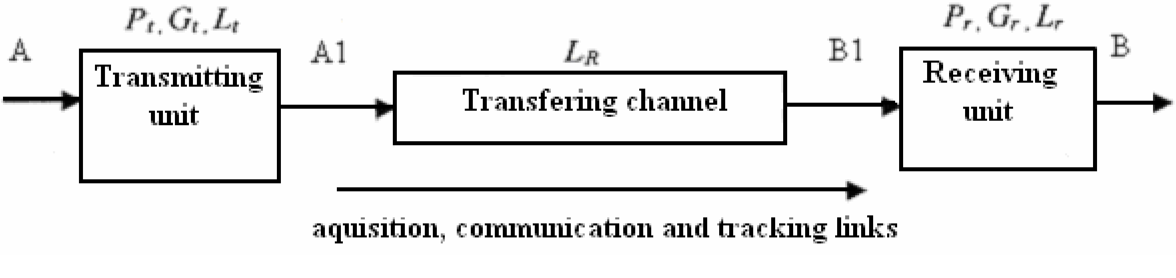

Fig.1 The model of signal transfer in LICS

2.1 The laser communication equation

This equation is used for analysis and optimization.

The equation starting with the transmit source power, the designer identifies all sources of link degradation (losses) and improvements (gains) and determines the received signal level. The laser communication equation (LCE) is very analogous to the link equation for any RF communication link. The link equation can be written as

$$P_r = P_t G_t L_t L_R G_r L_r \tag{1}$$

where:

P_r…the receive signal power (dB),
P_t…the transmitted signal power (dB),
G_t…the effective transmit antenna gain (dB),
L_t…the efficiency transmitter loss (dB),
L_R…the free space range loss (dB),
G_r…the receive antenna gain (dB),
L_r…the efficiency loss associated with the receiver (dB),
A…data from information supply,
A1…coded and modulated optical signal,
B1…optical signal before detection,
B…data for user [2].

There are determined signal sources, improvements (gains) and link degradation (losses) in this communication equation. The definitions of all parameters are not in this paper, but each entry into the link equation is given and verified in [3].

2.1.1 The free space range loss

The link range loss results from the diverging wave front of the optical energy as it traverses the link distance. The calculation of the classical range loss is given by

$$L_R = 10\log_{10}\left[\frac{\lambda}{4\pi R}\right]^2 \tag{2}$$

where:

λ...the wave length (nm),
R...the range between satellites

LICS parameters premises are optimized by computer programme, the premises consider two satellites in an orbit. For satellites at an altitude h above the Earth's surface and traversing circular orbits, the range between satellites is given as

$$R = \sqrt{2.(R_z + h)^2 + 2.(R_z + h)^2.(1 - \cos(\beta))} \tag{3}$$

where:

R_z… the Earth radius (m),
h… the altitude above the Earth's surface (m),
β… the orbital angle between two satellites.

You can see a figure 2 – the free space range loss is the curve of the free space range loss dependent on range between satellites. As you know the critical point of the losses during the signal transfer between two satellites is this parameter L_R.

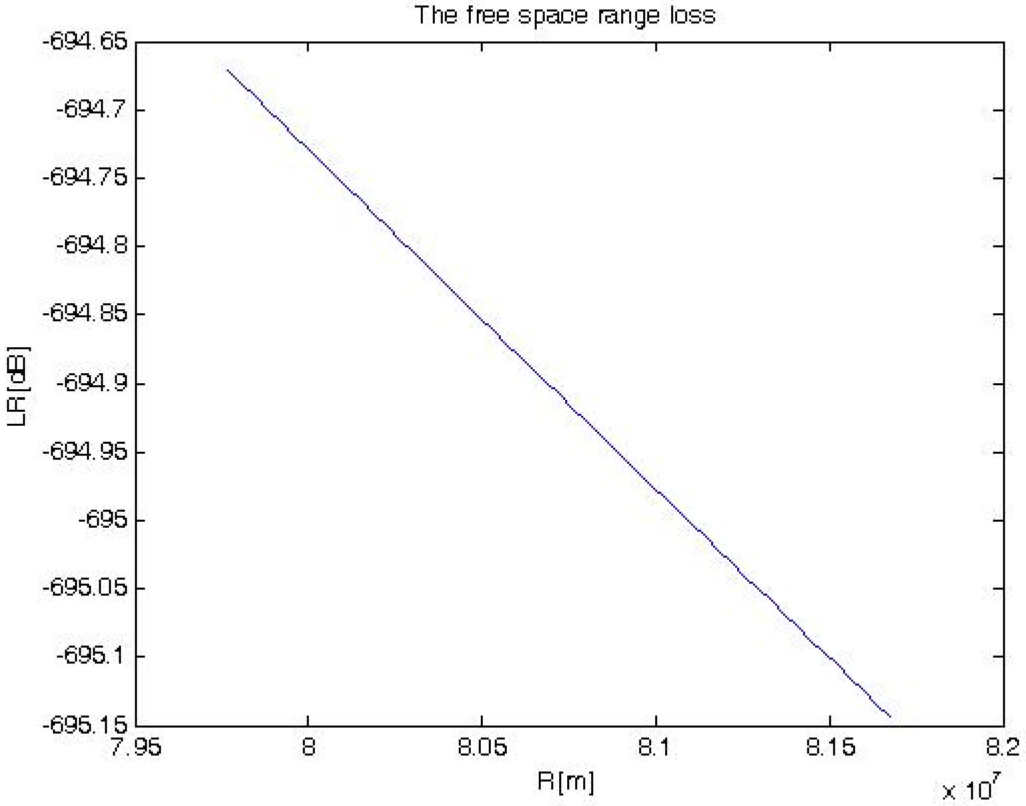

Fig.2 The free space range loss

3 Optical receiver

The scope factor depends on noises' limits. They are given by different factors. This paper shows more details from this area.
In an optical communication system, the function of the receiver is to convert a received optical signal into an electrical signal, which can serve as an input for other devices or communication systems.

The optical receiver basically consists of a receiving optics followed by a demodulator/detector. The latter may be based on incoherent or coherent techniques depending upon the type of modulation scheme used [4].

3.1 The detector's optical power

The receiver in a direct detection, diameter of the receiving antenna should be as large as possible to gather the maximum amount of signal energy [5].

3.1.1 The minimal value of power of receiving at the input of optical detector

The minimal value for this parameter is given as

$$P_{C\min} = \frac{\pi^2 \tau_t \tau_a \tau_r d_T^2 d_R^2 P_L}{32 R^2 \lambda_c^2} \qquad (4)$$

where:
τ_t…the coefficient of the transfer of transmitting subsystem,
τ_r…the coefficient of the transfer of receiving subsystem,
$\tau_a = \tau_{FS}$…the coefficient of the free space transferring,
d_T…the aperture diameter of the transmitting system,
d_R…the aperture diameter of the receiving system,
P_L…the laser power,
R…the range between transmitting and receiving units
λ_c…the optical wavelength of the carrier.

3.1.2 The maximal value of power of receiving at the input of optical detector

The maximal value for the power of receiving of optical detector can be characterized by

$$P_{C\max} = \frac{\pi^2 \tau_t \tau_a \tau_r d_T^2 d_R^2 P_L}{16 R^2 \lambda_c^2} \qquad (5)$$

There is a graphical output of comparison these parameters in figure 3.

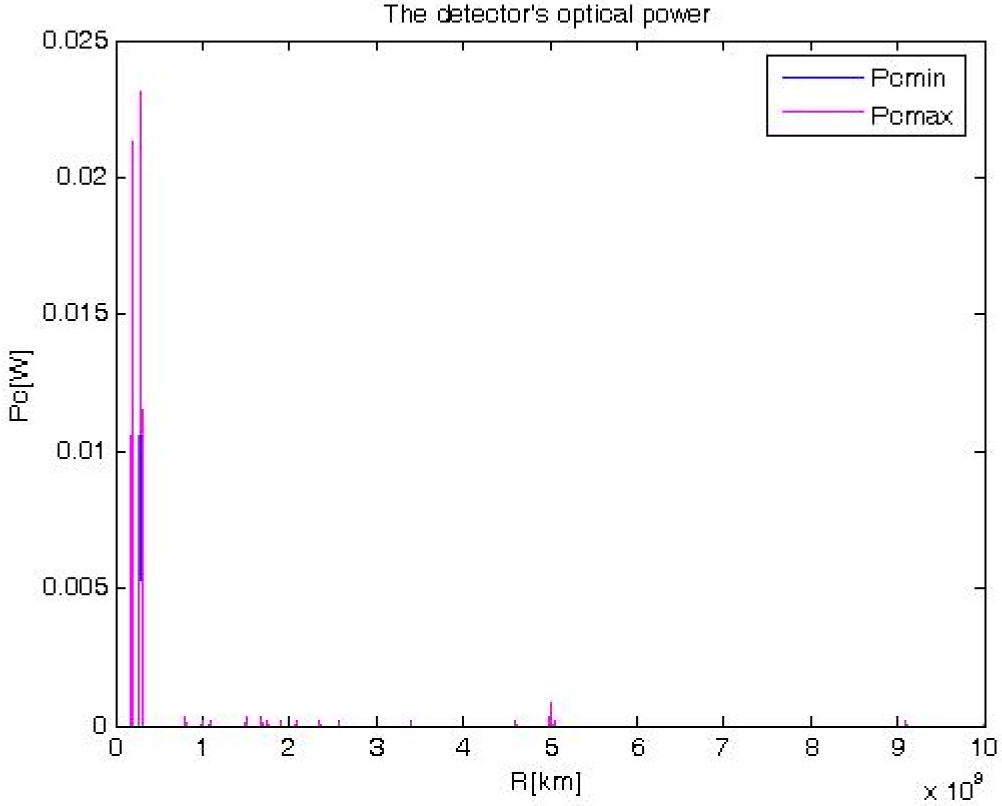

Fig. 3 The comparison of minimal and maximal value of power of receiving optical detector

3.2 Incoherent direct detection of optical carrier

The photo detectors used in optical space communications include PIN-photodiode, avalanche photodiode (APD), and photomultiplier tube (PMT) and photon counter. These detectors have their own merits and demerits.

For direct detection inter-satellite links based on Nd: YAG laser, detector used is either a PIN-photodiode or an APD [6].

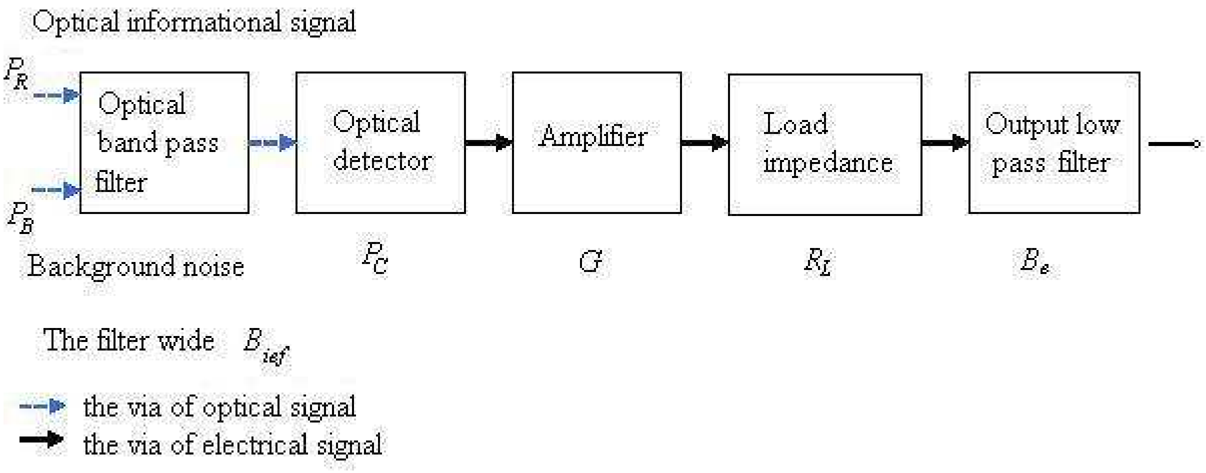

Fig.4 The schematic diagram of optical communication receiver – direct detection

B_0=B_e… the electrical bandwidth

The signal power S without modulation is given as

$$S = \frac{v_S^2}{R_L} = \left(G\alpha P_c\right)^2 R_L \qquad (6)$$

where:

v_s…the signal output from the circuit (the signal, which we can get after passing the output low pass filter),

R_L…the load resistance,

G…the circuit gain,

P_c…the power of receiving detector,

α…the coefficient of transformation.

This coefficient of transformation can be written as

$$\alpha = \frac{\eta q}{hf_c} = \frac{\eta q \lambda_c}{hc} \qquad (7)$$

where:

η…the efficiency,

q…the electronical charge,

h…the Planc constant,

f_c…the frequency of the carrier,

λ_c…the optical wavelength of the carrier,

c…the speed of light.

[7].

3.3 The noise in photodiodes

The main sources of noise are dark current noise, shot noise and thermal noise in a photodiode. There is one more source of noise due to random nature of the avalanche in an APD.

The dark current noise arises due to dark current which flows in the circuit when the photodiode is in unilluminated environment under bias condition. It is equal to the reverse saturation current of the photodiode. The magnitude of this current is strongly dependent on the operating temperature, the bias voltage and the type of detector. In an optical receiver, dark current sets a noise floor for the detectable signal power level. Therefore, it should be minimized by careful device design and fabrication. Dark current in optical telecommunication grade Si PIN-photodiodes is typically 100pA, while in Si APDs it is typically 10 pA. In InGaAs based PIN-photodiodes and APDs, the dark current is of the order of 100nA and it could pose a serious problem unless the device is cooled an appropriate temperature.

The shot noise arises from the statistical nature of the generation and collection of the photoelectrons when an optical signal is incident on photodiode. These statistics follow a Poisson process. Since the fluctuations in the number of photo-carriers generated from the photoelectric effect are a fundamental property of the photo-detection process, it will always exist. It thus set the lower limit on the receiver sensitivity when all other conditions are optimized. If dark noise current is large compared to signal current, signal current may be masked by the noise and therefore becomes unusable. On the other hand, if dark noise current is relatively small, it may have a negligible effect.

The thermal noise originates within the photodiode load resistance. Electrons within any resistors never remain stationary. They continuously move because of their thermal energy even with no applied voltage. The electron motion is random, so the net flow of charge could be towards one electrode or the other at any instant. Thus, a randomly varying current exists in the resistor [8], [9], and [10].

3.3.1 The powers of noises

There is an equation for the calculation of the power of the shot noise:

$$N_H = 2qG^2\left(I_P + I_B + I_D\right)B_e R_L \tag{8}$$

where:

q… the electronical charge,
G…the circuit gain,
I_P…the primary photocurrent,
I_D…the dark current,
B_e…the electrical bandwidth,
R_L…the load resistance,
I_B…the background current which can be given as

$$I_B = \alpha P_B \tag{9}$$

where:

α…the coefficient of transformation,
P_B…the background power.

Johnson's definition of the thermal noise can be simply written as:

$$N = N_H + N_T \tag{10}$$

N…the total noise,
N_H…the shot noise,
N_T…the thermal noise.

The signal to noise ratio is one of the most important parameters of the communication system. The value of this parameter can be optimized, but it is very difficult.

$$\frac{S}{N} = \frac{\left[\frac{G\eta q}{hf_c}\right]^2 R_L P_C^2}{2qB_e G^2\left\{\frac{nq}{hf_c}\left[P_C + P_B\right] + I_D\right\}R_L + 4kTB_e} \tag{11}$$

where is only a one unknown parameter:

T…the temperature of the system.

There can be three different relations for each of three different situations.

The first is: $N_T \gg N_H$, G=1:

$$\frac{S}{N} = \left[\frac{\eta q}{hf_c}\right]^2 \frac{R_L P_c^2}{4kTB_e} \tag{12}$$

The second is: $N_H \gg N_T$, G>>1:

$$\frac{S}{N} = \left[\frac{\eta}{hf_c}\right]^2 \frac{q}{2B_e} \frac{P_C^2}{\left\{\frac{nq}{hf_c}\left[P_C + P_B\right] + I_D\right\}} \tag{13}$$

The last is: P_B=0: it is theoretical situation for non-existing background optical power

$$\frac{S}{N} = \frac{\eta P_C}{2hf_c B_e} \tag{14}$$

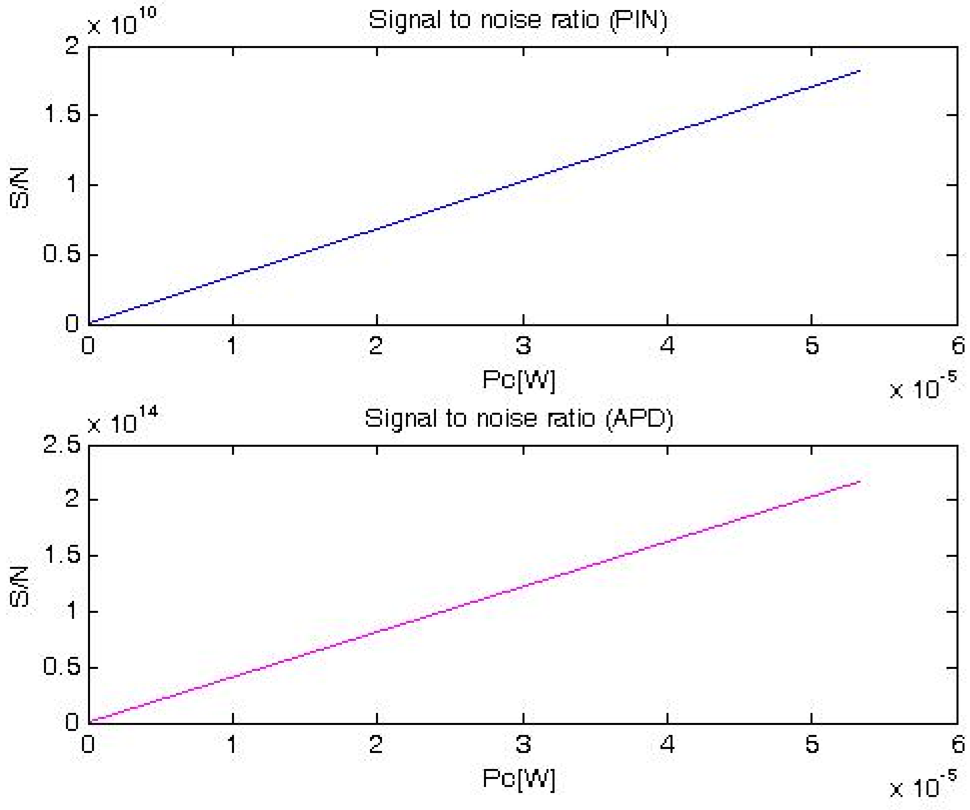

Fig.5 The comparison of differences between the used detectors (PIN/APD)

3.3.2 Incoherent direct detection (APD)

The shot noise is:

$$N_H = 2q(\alpha P_C)G_{APD}^{(x+2)}B_e \qquad (15)$$

The laser noise is:

$$N_L = 2qI_{LAPD}B_e \qquad (16)$$

The detector noise is:

$$N_D = 2qI_D G_{APD}^{(x+2)}B_e \qquad (17)$$

The transmitter noise is:

$$N_T = \frac{4kTB_eF_T}{R_L} \qquad (18)$$

where:

I_{LAPD}...the surface current,
G_{APD}...the gain of APD,
F_T...the noise figure of the electrical circuits.

The signal to noise ratio for APD is given as

$$\left(\frac{S}{N}\right)_{APD} = \frac{(\alpha P_C G_{APD})^2}{2q(\alpha P_C + I_D)G_{APD}^{x+2}B_e + 2qI_{LAPD}B_N + 4kTB_eF_T / R_L} \qquad (19)$$

There is a comparison of used detectors. You can see the differences between PIN and APD in the figure 5. The curves look very similar, but it can not been drown in one field, because the signal to noise ratio is much higher (high-order) for APD.

4 Conclusion

The space optical communication systems are very complex engineering systems, much more so than terrestrial fiber network. Proper design approaches need to e taken for their architectural construct and analysis. Breaking down the complex system into interacting but logically separate subsystems for their conceptual design and analysis is the key to success.

This paper simply describes the laser inter-satellite communication system and the problems with the noises´ limits.

The theory of these problems is briefly mentioned. Mathematical-physical basic description aforesaid system's aspects of the laser inter-satellite communication systems are in research work and are starting point for computer implementation programme several-parametric correlations [3]. The origin programme is made in MATLAB. The program is able to calculate selected several-parametric correlations and convert them in graphical outputs. We are able to indicate optimal values selected parameters of system transfer by enter criterions.

All parameters were calculated. The analysis and optimization were made from graphical outputs. The values of parameters are different for each links. Analysis and optimization supported by computer programme allow making cost-effective decision in designing individual parameters in laser inter-satellite communication system [2].

There are also the noises´ limits of the laser inter-satellite communication systems. The parameters for analysing and optimizing these systems were calculated in MATLAB programme too. The graphical outputs can be best results for the system optimizing and it is also very helpful for the comparison of different possibilities of the solution.

References:

[1]Lambert, S.G.-Casey, W.L.: Laser communication in space, Artech House Publishers, London 1995

[2]Smejkalova Mazalkova, M.: The system of laser inter-satellite communication, Advances in Communication, WSEAS Press, 2007

[3]Mazálková, M.- Titl, M.: Analýzy a optimalizace koncepcí laserového družicového komunikačního systému. (Analysis and optimization of conception of laser satellite communication system) Výzkumná zpráva (The research work). Univerzita obrany Brno, 2005.

[4]Franz, J.H.-Jain, V.K.:Optical communications-Components and systems, Alpha science International

[5]Katyman, M.: Laser Satellite Communication, Prentice-Hall, 1987

[6]Chinlon, L.: Optoelecrtonics technology and Lightwave Communication Systems, Van Nostrand Reinhold Company Inc., 1989

[7]Titl, M.: Systémové aspekty návrhu laserových kosmických komunikačních systémů. Podklady přednášek předmětu "Optické komunikace". (The System's Aspekts of Laser Space Communication Systems) VA, K-302, Brno.

[8]Li, T.: Advances in optical fiber communications: A historical perspektive. IEE J.SAC-1,(1983)

[9]Pal, B.P.(Editor): Fundamental of Fiber Optics in Telecommunication and Sensor, Wiley Eastern, 1994

[10]Smith, R.G.: Photodetectors for fiber transmission system, Proc. IEE, 68 (1980) 10.

[11]Vincent W.S.Chan.: Optical Space Communications; IEEE Journal on selected topics in quantum electronics, November/December 2000.