The system transfering between laser-satellites

MARKETA SMEJKALOVA MAZALKOVA
Department of Communication and Information Systems
University of Defence
65 Kounicova, 612 00 Brno
CZECH REPUBLIC
Marketa.Mazalkova@unob.cz

Abstract: Laser inter-satellite communication is on the verge of becoming a reality. It will be a key building block for wide-area space data networks of the future. Design methodologies treating these as complex engineering systems, and the technique to break down the systems into interacting but logically separate subsystems for design and analysis, will be suggested. The paper involves the introduction into laser inter-satellite communication system. The paper includes briefly analysis, optimization and subsystems design (three independent links) and system level development of signal transferring between two GEO 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.

Key-Words: Acquisition, tracking, data transfer, laser, satellite systems, laser communication, space channel

1 Introduction

The system engineering design methodology plays an important part in any systems implementation. Requirements must be clearly understood and analyzed and allocated to the functional elements, which are the building blocks of the system. Laser communication system design is not an exception to this disciplined approach.

A crosslink, or communication between two satellites, may be needed to solve certain requirements of satellite communication architecture. Laser communications offers the user a 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.

Most of the differences between laser communications and RF arise from very large difference in the wavelengths. RF wavelengths are thousands of times longer then those at optical frequencies.

2 Laser satellite communication systems

The laser communication equation (LCE) is a basic resort of LICS's (Laser Inter-satellite Communication System) analysis. 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. 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).

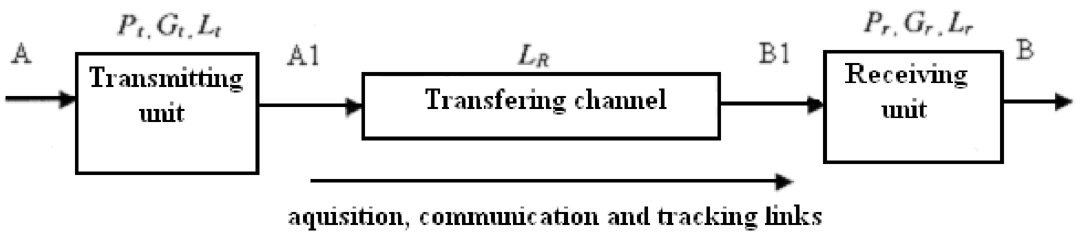

Fig.1 The model of signal transfer in LICS

The laser communication equation (LCE) can be written as

$$P_{t(dB)} = P_{r(dB)} - (G_{t(dB)} + \sigma_{ur(dB)} + L_{wf(dB)} + L_{t(dB)} + L_{R(dB)} + G_{r(dB)} + L_{r(dB)}) \quad (1)$$

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

This equation is used for analysis and optimization for each of three subsystems (independent links): Acquisition, Tracking and Data Transfer links. The system has to be optimized for all of these subsystems.

LICS parameters premises are optimized by computer programme, the premises consider two satellites in an orbit.

The transmitted signal power generated by the source is determined and entered into the link equation. Additional information about the bandwidth of the transmitted signal, pulse-width, extinction ration and wavelength are all gathered from the transmit source. This additional information is used in calculating the antenna gains and in determining the required signal.

The effective transmit antenna gain consists of three distinct parts. The first is the spatial distribution of energy in the far field, which is based on the aperture size, the near-field-energy profile, and the wavelength of the laser crosslink system. The second part involves the off-axis loss factor due to pointing errors in the optical system. The third is simply a geometric reduction of the far-field gain due to the wavefront errors determined above.

$$G_t = \frac{32}{\theta_{div}^2} \text{ (-, m, m)} \quad (2)$$

where: θ_{div}…full divergence angle

From scalar diffraction theory, the angular divergence of a plane wave spatially filtered by an aperture of diameter, a, is proportional to the wavelength, λ, and inversely proportional to the aperture size. This relationship can be described by the numerical expression:

$$\theta_{div} = \frac{4\lambda}{\pi a} \quad (3)$$

where: a… aperture of diameter and λ…wave length.

Link range loss results from the diverging wavefront of the optical energy as it traverses the link distance. The free space range loss can be simply written as

$$L_R = 10\log_{10}\left[\frac{\lambda}{4\pi R}\right]^2 \text{ (dB)} \quad (4)$$

where: λ…wave length, for real cases it is in dimension 780nm - 860nm.

For satellites at an altitude h above the Earth's surface and traversing circular orbits, the range between satellites is given as

$$R = \sqrt{2.(R_z + h)^2 + 2.(R_z + h)^2.(1 - \cos(\beta))}$$
$$\text{(m, m, m,}^0\text{)} \quad (5)$$

where: R_z…the Earth radius, β…the orbital angle between two satellites (for GEO, β =120°), h…the altitude above the Earth's surface.

Receive antenna gain is calculated from the antenna gain is calculated from the collecting area of the antenna and the wavelength of the incident optical energy and is expressed by a unitless parameter as

$$G_r = \left[\frac{\pi D_{aper}}{\lambda}\right]^2 \quad \text{(-, m, m)} \qquad (6)$$

where: D_{aper} …the aperture diameter.

Receiver optical losses - before the optical transmission at the wavelength of operation is required to be estimated using good design practices, superior optical coatings, and the number and type of optical surfaces being traversed. Each optical surface contributes a multiplicative loss factor to the overall transmission budget. This loss factor degrades the transmit power by the derived factor.

Receiving pointing loss – similar to the loss associated with the transmitter pointing error, a loss term must be considered for the mispointing at the receiver. For direct-detection links, this is normally not a concern since the receive FOV and spot size are oversized and not diffraction-limited.

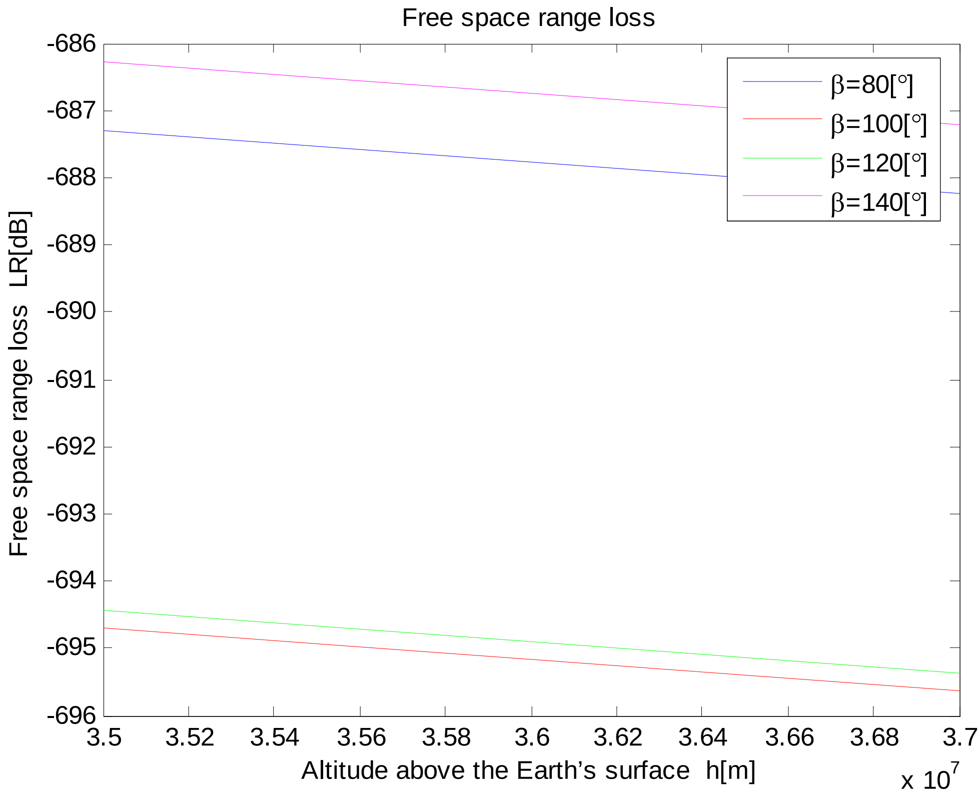

Fig. 2 Free space range loss

2.1 Acquisition link

Acquisition requires searching the uncertainty area to locate and establish the link between satellites.

The convergence link is not dominated by the excess communication channel shot noise, as the tracking link. The difference in required signal when the communication channel excess noise is removed is on the order of 3 dB.

The square root of the laser powers yields the divergence widening factor is

$$F_{DIV} = \sqrt{1.93.\frac{P_{t-com}}{P_{t-trk}}} \quad \text{(-, W, W)} \qquad (7)$$

where: $P_{t\text{-}com}$ … the maximal power of laser sources, $P_{t\text{-}trk}$ … the power of source of the tracking link.

Acquisition is accomplished using a pilot signal, easily recognizable and detectable receiver.

The figure 3 – the acquisition is always detectability within some timeframe. It includes both spatial and temporal detection. The receiving system must detect line of sight. This takes a few iterations of detections and a reasonable bandwidth of received signal to allow angular control of return beam. The acquisition is affected by free-space range loss. The figure 3 – there is a graphical output from original program. You can see the curve for transmitted signal power of tracking link – there is a dependence of two parameters-required signal power and detector responsivity. These parameters are used for calculation of signal transfer power. Detector responsivity is calculated from:

$$Rd = \frac{nq\lambda}{hc} \quad \text{(A/W,-, C, m, J/sec, m/sec)} \qquad (8)$$

where: η…the quantum efficiency, q…the electron charge, λ…the wavelength, h…the Planc's konstant.

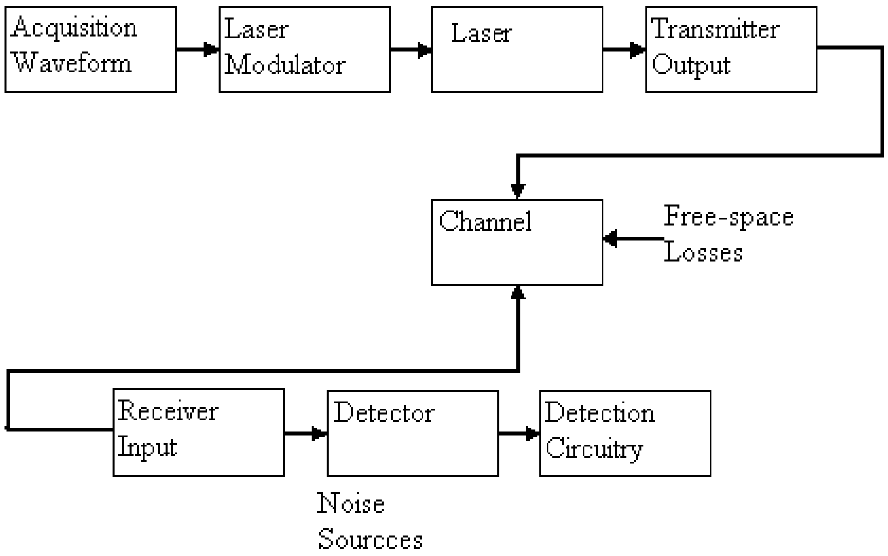

Fig. 3 Acquisition link model

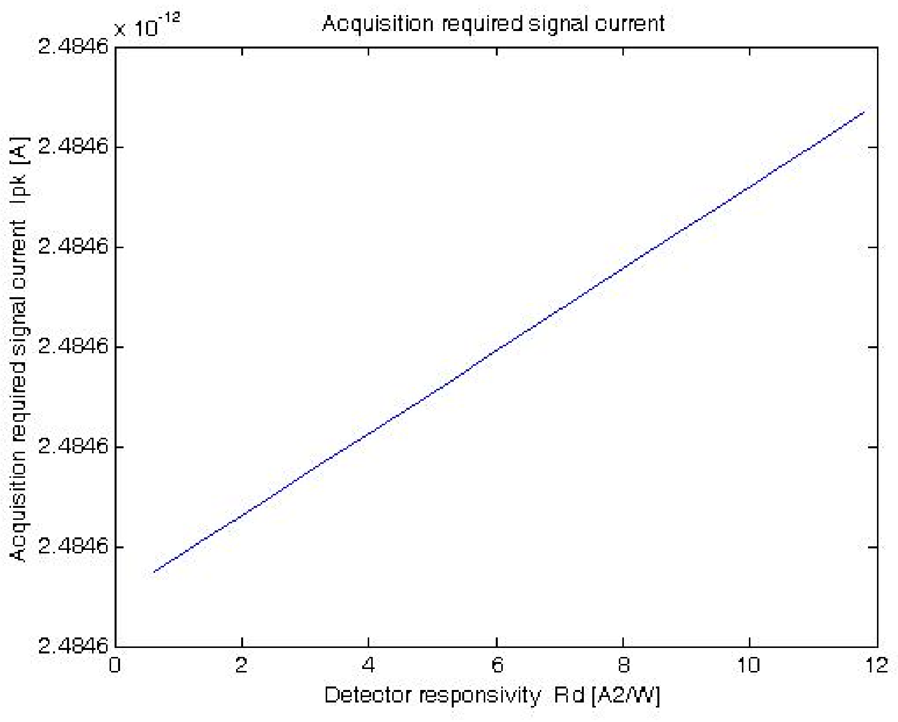

Fig. 4 Required signal current of acquisition link

2.2 Tracking link

Tracking link model are shown in figure 5. The critical figure of merit for tracking links is the noise equivalent angle (NEA). The NEA is defined as the residual tracking error along the line-of-sight vector to the companion satellite. The NEA is the function of the received signal to noise ratio (SNR) in the tracking bandwidth, the optical spot size on the detector, and the gain of the tracking system.

The required signal for the tracking system is directly related to the tracking noise established by the budget developed earlier. Based on the required noise equivalent angle and the angle slope factor, the required signal is calculated from:

$$I_{pk-trk} = \frac{2qFB.(1+1/N_e)}{(SF.\sigma_{rms})^2.(1-1/N_e)^2} + \sqrt{\left[\frac{2qFB.(1+1/N_e)}{(SF.\sigma_{rms})^2.(1-1/N_e)^2}\right]^2 + \frac{4.\sigma_{total-trk}^2.B}{(SF.\sigma_{rms})^2.(1-1/N_e)^2}} \quad (9)$$

where: q…the quantum charge, F…the noise factor of the detection process, B…the electrical bandwidth, N_e…the extinction ratio for a square-wave tone, SF…the angular slope factor, σ_{rms}…the noise equivalent angle NEA, $\sigma_{total-trk}$…the total noise density for tracking.

$$P_{t-trk(dB)} = P_{r-trk(dB)} - \begin{pmatrix} G_{t(dB)} + (\sigma_{ur})_{(dB)} + L_{wf(dB)} + \\ L_{t(dB)} + L_{R(dB)} + G_{r(dB)} + L_{r(dB)} \end{pmatrix} \quad (10)$$

where: P_{t-trk}…the transmitted signal power of tracking ling, P_{r-trk}…the received signal power of tracking link.

The figure 6 – there is a graphical output from original programme for optimization. The curve shows us the dependence of transmitted signal power on divergence factor. It is for tracking link.

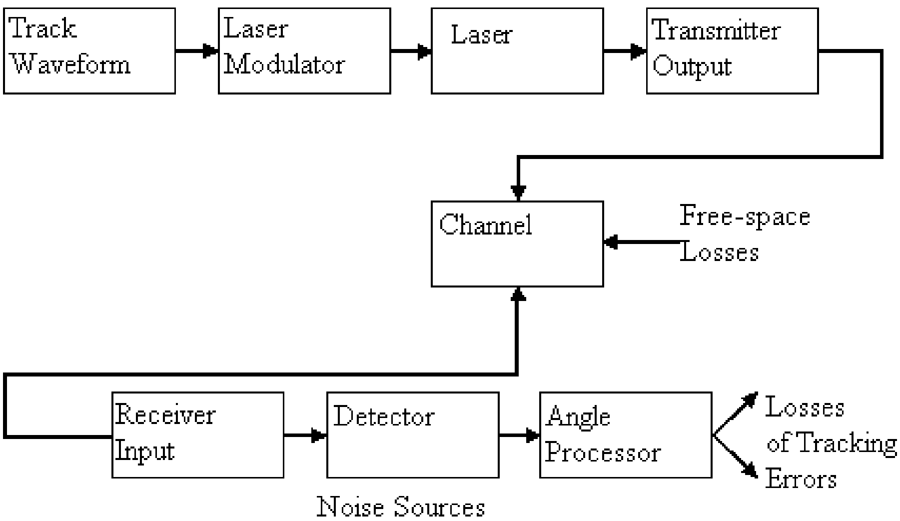

Fig. 5 Track link model

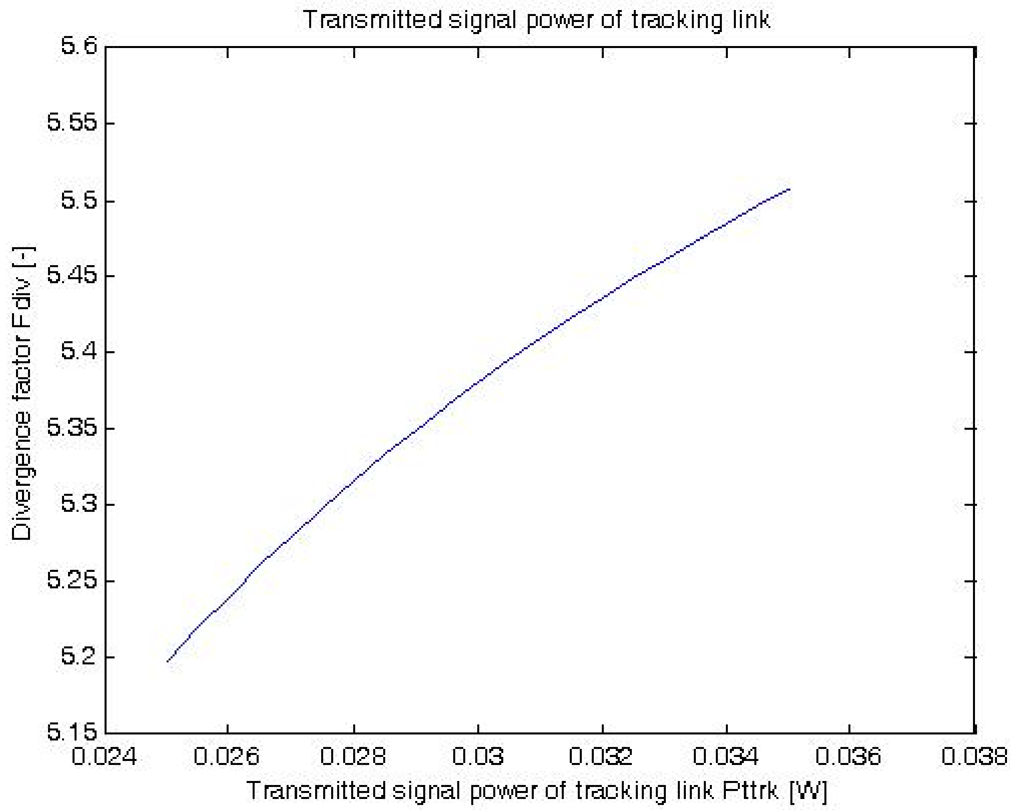

Fig. 6 Transmitted signal power of tracking link

2.3 Transfer link

This is a link for the data transfer from one satellite to its companion. Optical source and modulation have to be carefully examined to determine best modulation approach for each source. The receivers have to be matched to the type of modulation used. The data transfer link model is shown in figure 7. Background energy, in the direct - detection case is a contributor to the system sensitivity. The figure 8 – the same situation like on the figure 6. Instead of tracking link, this is the figure of data transfer link.

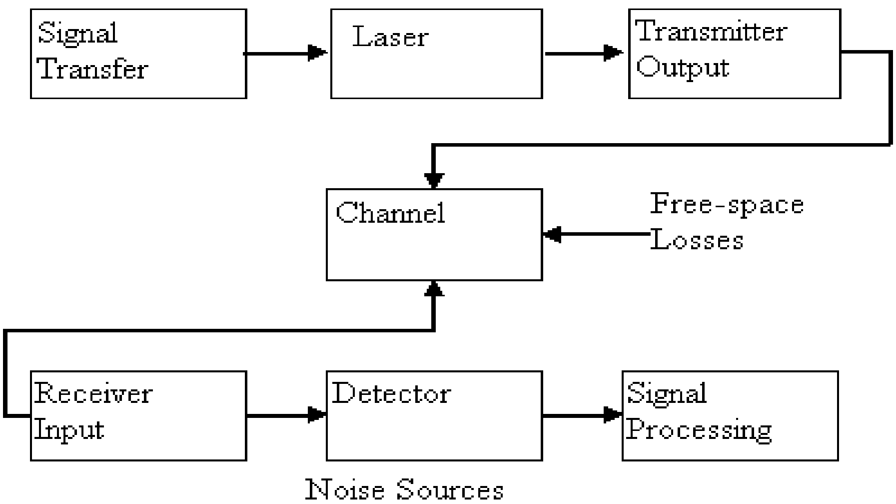

Fig. 7 Data transfer link model

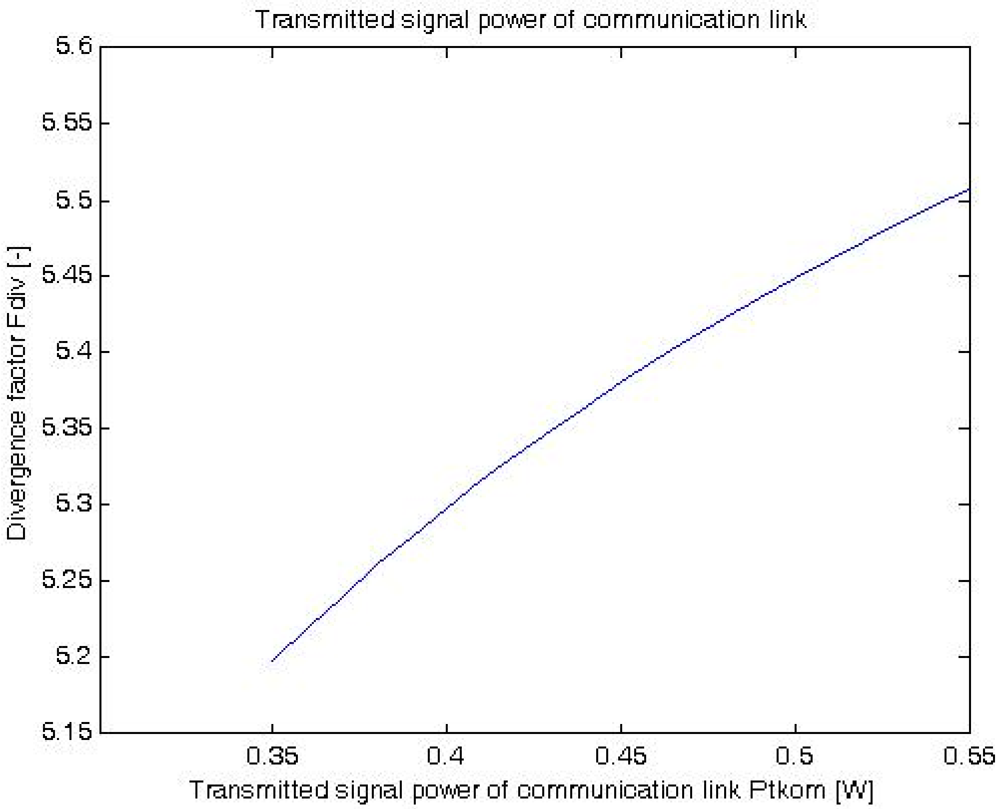

Fig. 8 Transmitted signal power of communication link

3 Mathematical and physical implementation analysis and optimization of inter-satellite communication system in MATLAB

Bearing in mind the main research objective, partial goals have been defined. These goals include mathematical and physical analysis of basic parameters and characteristics for LICS design that is required for communication and control signals transfer between GEO satellites. This analysis is also needed for LICS technological basis design. Finally, it is also necessary for computer implementation of several-parametric correlation into analysis and optimization in MATLAB programme. Analysis and optimization is given by the graphical outputs that enable LICS parameters optimization occurring in actual situation.

The original research study [1] is over 90 pages long, so it is impossible to mention all relevant data in this paper. It includes a programme for the input parameters design, for the input and output losses, as well as free space losses.

Basic mathematical and physical description aforesaid system aspects are dealt with in research study [1] and they serve as a starting point for computer implementation of several-parametric correlation programme.

The equations which were used in the calculations and in graphical outputs of parametric correlations of LICS system optimization are given at the end of this paper.

The original programme has been prepared in MATLAB. The programme is able to calculate selected several-parametric correlations and to convert them into graphical outputs. We are able to indicate optimal values of selected system transfer parameters according to specified criteria.

4 Summary

The original research study [1] is over 90 pages long, so it is impossible to mention all relevant data in this paper. The research study includes mathematical and physical analysis of basic parameters and characteristics for LICS design that is required for communication and control signals transfer between GEO satellites; computer programme for the input parameters design, for the input and output losses, as well as free space losses. The programme is able to calculate selected several-parametric correlations and to convert them into graphical outputs. We are able to indicate optimal values of selected system transfer parameters according to specified criteria.

Mathematical-physical basic description aforesaid system's aspects 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 [4].

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