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ENHANCEMENT OF COMMUNICATION QUALITY IN THE X-BAND DOWNLINK CHANNEL FOR LEO EARTH OBSERVATION SATELLITES

Introduction. *Earth observation by low Earth orbit (LEO) satellites plays a critical role in supporting various sectors of the national economy. To increase the efficiency of this technology, optimizing the video data downlink — particularly with respect to the satellite's elevation angle relative to the ground station — is essential.*

Problem Statement. *The communication link margin varies depending on the selected signal waveform, while changes in the satellite's elevation angle alter the propagation path length and, consequently, the energy characteristics of the downlink. For small satellites such as CubeSats, which have limited onboard power, the potential to transmit high-data-rate video within a brief communication window — depending on modulation mode — has not been sufficiently studied.*

Purpose. *This study aims to enhance the performance of Earth remote sensing systems by improving the energy efficiency and throughput of satellite-to-ground video transmission in the X-band.*

Materials and Methods. *The analysis applies microwave communication theory to evaluate the energy budget of the downlink, incorporating Adaptive Coding and Modulation (ACM) techniques supported by the DVB-S2/S2X standard. The study considers various modulation and coding (MODCOD) schemes and output power levels at different satellite elevation angles.*

Results. *The energy margin of the LEO satellite downlink has been calculated, enabling an assessment of the feasibility of using DVB-S2X for video transmission from Earth observation satellites. The findings have shown that at low elevation angles, a connection can be established using the most robust mode (QPSK 1/4), supporting a data rate of 38 Mbps. At elevation angles exceeding 50 degrees, higher-order modulation such as 32APSK 9/10 becomes feasible, achieving data rates up to 384 Mbps.*

Conclusions. *The study has demonstrated that applying the DVB-S2(X) standard to CubeSat-class Earth observation missions enables more efficient and adaptive use of the X-band downlink channel. This approach has improved flexibility and throughput of video data transmission, especially when tailored to satellite elevation angles.*

Keywords: satellite communications, Earth observation, X-band, DVB-S2X, link margin, CubeSat, LEO, adaptive modulation.

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Nomenclature

A is a total atmospheric attenuation excluding flicker attenuation;
C/N_0 is carrier-to-noise density ratio;
E_b/N_0 is signal-to-noise density ratio;
G_{Ar} is gain of the receiving antenna;
G_{Ar}/T_S is receiver figure of merit;
L_{fr} are losses in the antenna-feeder path of receiving a ground station;
L_{FS} is path loss of free space;
L_{ft} are losses in the antenna-feeder transmission path of the on-board transmitter;
P_n is noise generated at the input of the satellite receiver of the ground station;
P_r is power at the receiving station;
P_t is power of the on-board transmitter;
T_A is equivalent antenna noise temperature;
T_S is total equivalent noise temperature of the receiving system.

Abbreviations

ACM — Adaptive Coding and Modulation;
ASM — Attached Synchronization Marker;
CCSDS — Consultative Committee for Space Data Systems;
COTS — Commercially available off-the-shelf;
DVB-S2X — is an extension of DVB-S2 satellite digital broadcasting standard;
EO — Earth Observation;
ETSI — European Telecommunications Standards Institute;
FEC — Forward Error Correction;
HDT — High-speed Data Transmitter
LDPC — Low-Density Parity Check;
LKM — Link Margin;
LNA — Low-Noise Amplifier;
MODCOD — changing modulation and coding;
QPSK — Quadrature Phase-Shift Keying;
VCM — Variable Coding and Modulation.

Remote sensing of the Earth significantly contributes to the development of many branches of the economy of our country. To improve the remote sensing of the Earth, it is necessary to optimize the video data transmission channel in terms of determining the satellite position angle.

In work [1], the concept of the CubeSat platform for scientific missions around the Earth was proposed for the first time. Until now, this concept has been successfully developing [2—5]. Currently, such satellites using to perform various tasks: for voice communication in the VHF/UHF range [2]; for the study of cosmic radiation [3]; for use in NASA networks [4]; for Earth observing [5]. The use of COTS systems makes it possible to significantly reduce the cost of the implementation of small satellites [2]. When implementing this class of satellites, an additional comprehensive analysis of the communication channel of the specific frequency range on which this spacecraft operates is necessary [4].

Regardless of the class of the satellite, when analyzing the communication channel, one should always consider the peculiarities of signal propagation on the “spacecraft — earth station” line. It is a well-known fact that the key factor for the successful execution of a flight mission is the availability of high-quality control and telemetry control of an unmanned aerial vehicle, which in turn are determined by a fail-safe radio communication between a ground station and an unmanned aerial vehicle [6].

Attenuation in rain is a major factor in estimating the communication energy budget for satellite communication systems. Scattering and absorption are major concerns for system designers in all frequency bands used in satellite communications. This leads to the need to construct appropriate communication channel models that allow accurate estimates of rain attenuation based on available information on rain attenuation characteristics [7—10]. It is also necessary to evaluate local precipitation statistics, which is the key to predicting the impact of rain on the propagation of electromagnetic waves in the atmosphere [11—12].

Atmospheric gas attenuation and related frequency-dependent effects are also considered under the calculation [13]. The communication channel model should consider the apparent angle of the space station site, considering atmospheric refraction [14]. Methods for calculating the refraction correction for the elevation angle of the annual mean global reference atmosphere should be used here.

The so-called background noise level at the earth station location is important to ensure compliance with electromagnetic compatibility requirements. This is especially true for small satellites that have technical limitations on the output power of the transmitter on the satellite. To ensure a sufficient signal-to-noise ratio, the minimum signal power that the satellite emits is most often calculated based on existing noise levels [15—17]. It should be emphasized that different COTS systems have various levels of internal noise. Therefore, the radio communication channel budget is calculated for a specific communication system.

In this paper, the authors investigate the peculiarities of signal propagation in the downlink of the EO satellite system. The purpose of the work is to improve the system of remote sensing of the Earth. To achieve the purpose, it is necessary to investigate the dependence of the potential speed of video information signal on the position angle of a small satellite with COTS components to improve the quality of communication when transmitting video information of remote sensing of the Earth.

It is known that the energy budget of the “satellite-earth station” radio line depends on various factors. In particular, the use of different signal forms involves different values of the link margin. On the other hand, a change in the observation angle of the satellite relative to the earth station changes the length of the route that the signal travels and accordingly changes the energy characteristics of the communication line.

The work [18] proposed an X-band high-speed data transmitter (HDT) design for transmitting information from a small satellite to an earth station. At the same time, it was emphasized that the proposed HDT allows changing the operating modes depending on the conditions of information signal propagation, with the aim of transmitting a large volume of video data in a short communication session. Therefore, it is of interest to investigate the possibilities of transmitting an informational video signal from a small EO satellite to an earth station, depending on the selected mode of video signal formation, on the physical characteristics of the environment on the line “spacecraft — ground station” and on the angle of the satellite at the receiving location.

Due to change of the electromagnetic situation on the earth’s surface, several works express the opinion of changing the calculation methodology of the link margin [7]. This is especially true for the K_a-band. On the other hand, in some works, the existing methods of considering atmospheric phenomena, such as showers, are questioned. This applies to areas of Asia and Africa where there are instant showers with many raindrops. However, the general trend of these works [7—12] is that the existing methods, which were developed by the ITU over the last one and a half dozen years and are pleased by the influence of various atmospheric phenomena, have not yet lost their relevance.

In work [18] a communication system with a high data transfer rate is proposed, which can be applied to small EO satellites with COTS components. Therefore, in the development of this study, it is necessary to consider the issue not of changing the basic principles of the proposed communication system, but of conducting research on the introduction of additional modes and expanding the range of parameters of the information transmission system. An additional argument for continuing this research is the use of hardware and software that can be purchased from commercial suppliers without the need for special development or modification. As a result, it allows significantly reducing the financial costs of the satellite project.

There are several prospects for using DVB-S to transmit large data sets from EO satellites. DVB-S is an open-source standard. This means it is free to use. In the conditions of a limited budget for the development of small EO satellites, this is a very important factor.

DVB-S supports data transmission in high quality and at high speed. This allows efficient transfer of large data sets, including high-resolution images. In addition, DVB-S can be used for data

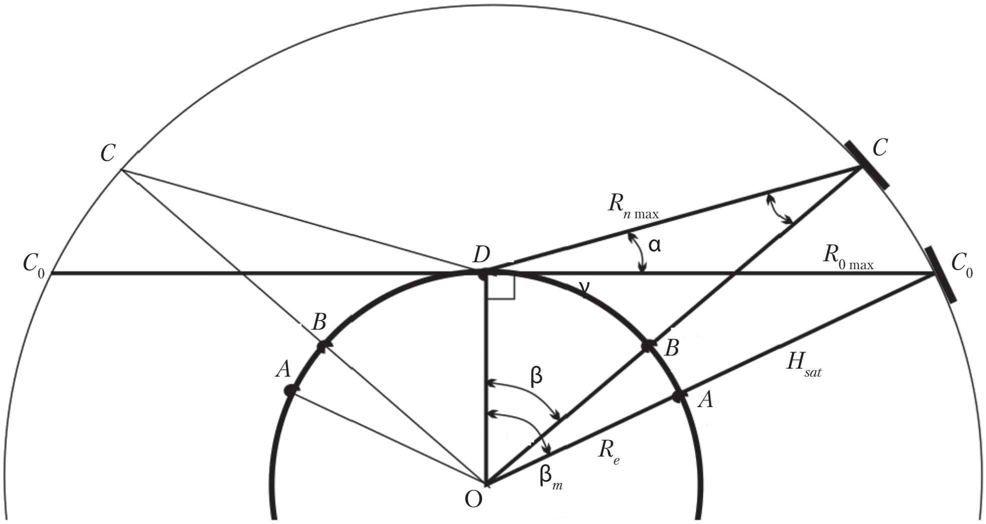

Fig. 1. Calculation of satellite orbit parameters

transmission over long distances. This is important for EO satellites that are in LEO. In addition, it should be noted that several modulators and demodulators of the DVB-S standard are industrially produced.

The data collected by the on-board camera of the EO satellite are processed, stored, and transmitted together with the main telemetry data in the range of 8025—8400 MHz (X-band) to the corresponding ground stations [18].

The technical characteristics of the X-band high-speed transmitter developed in [18] are as follows: the frequency range is 8025 to 8400 MHz; the altitude of the satellite's orbit is from 400 to 600 km; operating temperature range –40 °C/+50 °C; power supply range 21/35 V; consumed power <40 W; RS485/CAN control and telemetry interface; output RF power 1 W (per polarization); the gain factor of the satellite antenna is 15 dBi; DVB-S2 modulation, MODCOD 1—28; data transfer rate 1—70 ms/s per channel; GTx interface.

The DVB S2(X) standard is used to transmit frames according to CCSDS. The interface between CCSDS and DVB-S2(X) is based on ASM and SMTP.

DVB-S2(X) is used in the adaptation profile [18] as a complete and self-sufficient standard, and the definitions and specifications taken from DVB-S2(X) are only applicable in the context of this experimental specification. However, individual functions or components of DVB-S2(X) (eg VCM/ACM, 8PSK and higher order modulations) may be reused, redefined and/or redefined by CCSDS in other recommended or experimental standards. Under the work, the peculiarities of the DVB-S2(X) standard regarding video image transmission during EO were considered. The advantages of the DVB-S2(X) standard were implemented in X-band HDT [18]. However, the literature sources lack comprehensive data on the conditions of information signal propagation from the developed HDT to the earth station depending on the MODCOD, on the propagation conditions on the communication line and on the satellite position angle.

Due the work, the technical implementation of the downlink of the X-band payload [18] was considered. For its analysis, the classical theory of building radio communication in the microwave range is used. This line has double polarization with three frequency channels per polarization. Each polarization has a special power amplifier, and each frequency channel has a special modulator.

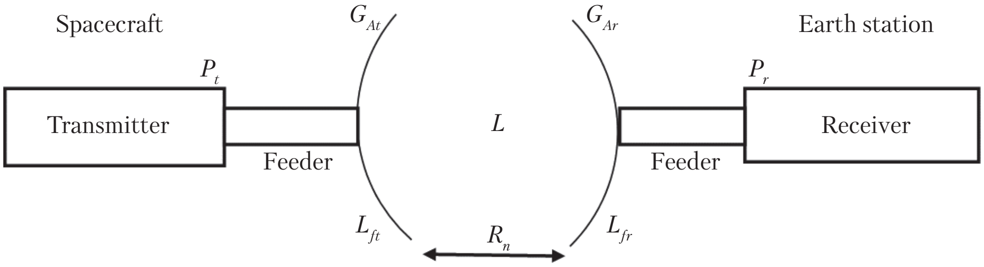

Fig. 2. Structural diagram of the spacecraftearth station radio communication channel

When calculating the energy balance of the radio line, recommendations [19] and general ITU recommendations were considered.

Consider the field of view (radio visibility) of the EO satellite (Fig. 1). Radio visibility is the area of the Earth's surface where you can observe this satellite and receive its signals.

The field of view is limited by the true horizon line, so its size depends on the height of the satellite, characterized by the angle $H_{sat}\beta_m$ and the corresponding arc *ADA* (Fig. 1) on the surface of the Earth, which can be characterized by the radius of the field of view $R_{0\max}$. The following formula is used here

$$\beta_m = \arccos\left(\frac{R_e}{R_e + H_{sat}}\right).$$

The on-board receivers of the satellite system provide the specified measurement accuracy in the field of view limited by the radio horizon, which rises for users to the angle α (the minimum elevation angle of the access point). At the same time, the field of view is determined by the angle ($\beta < \beta_m$)

$$\beta = \arccos\left(\frac{R_e \cos\alpha}{R_e + H_{sat}}\right) - \alpha.$$

The maximum slant range is the distance between the location of the access point (point *D*) and the location of the satellite (point *C*)

$$R_{n\max} = \sqrt{R_e^2 + (R_e + H_{sat})^2 - 2\cos(\beta)(R_e + H_{sat})}.$$

Structural diagram of the "spacecraft — earth station" radio communication channel is shown on Fig. 2.

The paper proposes to use the DVB-S2(X) standard for small satellites manufactured using CubeSat technology to improve the quality of communication in the satellite channel, to ensure more flexible and efficient transmission of video data.

For the spacecraft — earth station line, the signal strength at the input of the earth station receiver can be determined from the first transmission equation:

$$P_r = P_t - L_{ft} + G_{At} - L_{FS} - L_{add} + G_{Ar} - L_{fr}.$$

The complete attenuation of radio signals in satellite communication lines is determined by losses in free space and additional losses due to the peculiarities of the functioning of satellite communication systems:

$$L = L_{FS} + L_{add}.$$

The attenuation of a signal in free space is calculated using the following formula

$$L_{FS} = 20\lg\left(\frac{2\pi R_{n\max}}{\lambda}\right).$$

When designing communication lines "spacecraft — ground station" for communication systems, it is necessary to consider the peculiarities of electromagnetic wave propagation.

When performing the calculation, only the influence of the troposphere on the useful signal was taken into account, namely: microwave interference between stations located on the Earth's surface; interference between stations in space and stations on the Earth's surface. Coordination between earth stations operating in bidirectionally distributed frequency bands was not considered.

Propagation losses of radio waves on the "spacecraft — earth station" path is the result of the combined action of various factors, namely: attenuation in atmospheric gases; attenuation during rain, other precipitation, and clouds; focusing and defocusing of the antenna beam; reduction of the gain of the antenna due to the incoherence of the wavefront; flickering and multi-beam phenomena; attenuation of the signal due sand and dust storms.

In an ideal case, weather parameters are measured locally at a specific location and these parameters are a function of the altitude of the earth station location relative to sea level. In the absence of local measurements, the ITU provides ideal atmospheric parameters. Then the attenuation in atmospheric gases is defined as:

$$\gamma = \gamma_0 + \gamma_w .$$

Using the methodology [20], it is possible to calculate the total attenuation on the line "spacecraft — earth station" at the full zenith angle (elevation angle equal to 90°). This attenuation is

$$L_{az} = \gamma_0 h_0 + \gamma_w h_w .$$

Using known literature sources, it is possible to determine the total attenuation at the zenith at sea level, as well as the attenuation in dry air and water vapor obtained for the annual mean global reference atmosphere. Then the specific attenuation due to atmospheric gases for the S-band is $L_{az} = 4 \cdot 10^{-3}$ dB/km, and for the X-band is $L_{az} = 1 \cdot 10^{-2}$ dB/km.

For line "spacecraft — earth station" with elevation angles in the range 5° to 90°, the simple cosecant law can be used to calculate the total slant path gaseous attenuation L_α [20]:

$$L_\alpha = \frac{L_{az}}{\sin\alpha} .$$

Attenuation in atmospheric gases at frequencies below 10 GHz can usually be neglected. Attenuation in precipitation and clouds is calculated according to general ITU recommendations. This allows obtaining the value of long-term statistics of the slant-path rain attenuation for a given location at frequencies up to 55 GHz. The calculations considered the rain intensity $R_{0.01}$ at the location of the earth station. The map of rainy climate zones was also used.

Additional energy losses can occur due to antenna point loss [21—23]. These losses depend on the method and design (including the mechanical part) of the antenna device. Antenna point loss consists of the losses of the transmitting and receiving antennas. A typical pointing loss of a terrestrial antenna tracking a satellite is 0.3 dB. In the worst conditions from the point of view of guidance losses, the situation is considered when the satellite is on the border of the service area. In this case, the total losses of the antennas will be 3.3 dB. Thus, antenna point losses are within limits: $L_{acc} = 0.3 \div 3.3$ dB.

Thus, additional attenuation of the radio signal on sections of the radio line depends on many factors that appear independently of each other and can be represented as the sum of attenuations associated with the main factors:

$$L_{add} = L_\alpha + L_{rain} + L_{acc} + L_{pol} .$$

To estimate the energy potential of the transmission station, the concept of equivalent *EIRP* was introduced. Then the power at the receiving station is expressed as

$$P_r = EIRP + G_{Ar} - L_{FS} .$$

Let us evaluate the influence of the main parameters of the transceiver equipment on the bandwidth of the binary communication channel, assuming that the bandwidth of the transmitter and receiver is consistent with the frequency bandwidth of the transmitted useful signal. Then, in the general case, the power at the receiver input is calculated using the Friis radio transmission equation.

The power of the noise generated at the input of the satellite receiver of the ground station by various sources can be determined by the formula:

$$P_n = k T_S \Delta f .$$

The calculated total effective temperature of the receiving devices is transferred to the irradiator of the receiving antenna.

Under the calculations, it was considered that the spectrum width of the modulated radio signal depends on the roll-off factor, constellation, and code rate.

The total equivalent noise temperature of the receiving system, consisting of the antenna, the

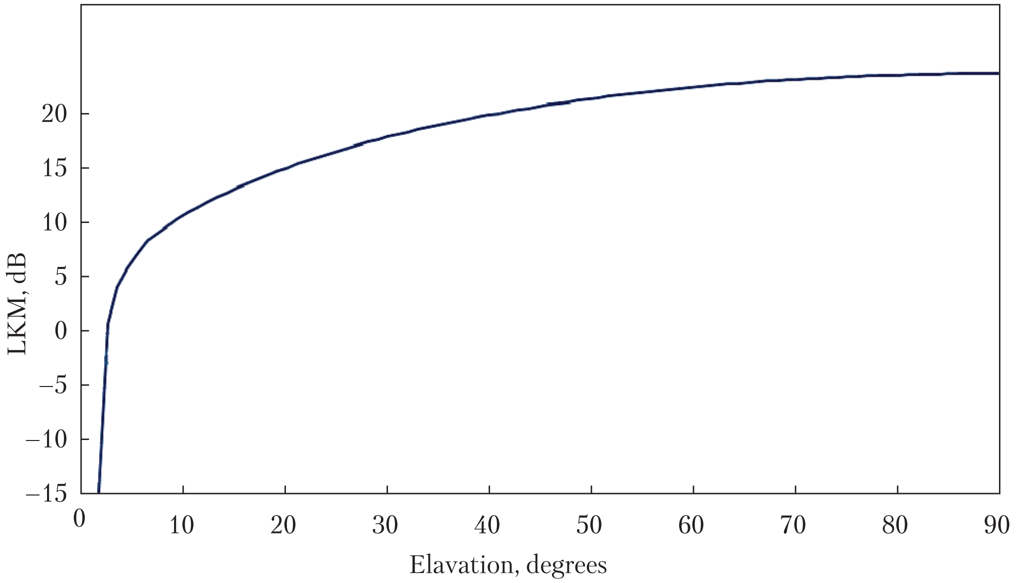

Fig. 3. Dependence of LKM on the satellite position angle (elevation) for MODCOD = 1 (QPSK 1/4)

waveguide path, and the receiver itself, reduced to the input of the receiver:

$$T_S = T_A \eta_B + T_0(1-\eta_B) + T_{LNA}.$$

Then the equivalent noise temperature of the antenna can be represented as

$$T_A = T_{\cos} + T_{CFA} + T_e + T_{re} + T_{na} + T_{af}.$$

The constituent components of the noise temperature are determined by a range of factors. The noise environment at stations on the surface of the Earth and in space is described in detail in [23].

The evaluation of the communication line “spacecraft — earth station” was conducted. If the attenuation of the signal transmitted from the transmitter on board the spacecraft to the receiver near the Earth’s surface is known, then an estimate of the brightness temperature (i.e., sky noise) at frequencies from 2 to 30 GHz in the direction of the propagation path from the signal can be obtained by the formula:

$$T_{sky} = T_{mr}(1-10^{-A/10}) + 2.7\cdot 10^{-A/10}.$$

If the temperature T_S is known, then the average radiation temperature T_{mr} for clear and cloudy weather can be estimated as follows:

$$T_{mr} = 37.34 + 0.81\ T_S.$$

If local data are not available, the mean ambient radiation temperature, T_{mr}, of 275 K can be used for clear and rainy weather.

The concept of receiver figure of merit was used to characterize the energy potential of the receiving device

$$[G_{Ar}/T_S]_{dB/K} = G_{Ar} - T_S.$$

Note that the equivalent noise temperature of the receiving system depends not only on the inherent noise characteristics of the antenna and receiver, but also on external noise sources. The receiver figure of merit does not objectively reflect the quality of the receiving equipment and may change depending on operating conditions. For this reason, these conditions are usually indicated in reference literature (for example, when the sky is clear and the angle of elevation of the antenna is not less than specified).

To ensure the necessary quality of digital information transmission, it is necessary to maintain a clearly defined threshold ratio of the bit energy E_b to the noise power spectral density N_0 (E_b/N_0) [24—25].

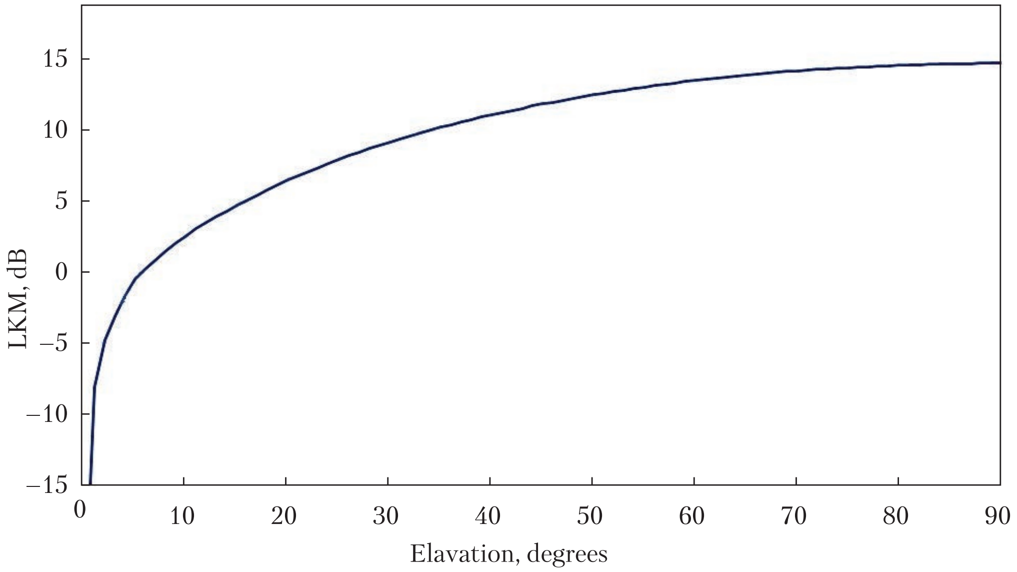

Fig. 4. Dependence of LKM on the satellite position angle (elevation) for MODCOD = 13 (8PSK 2/3)

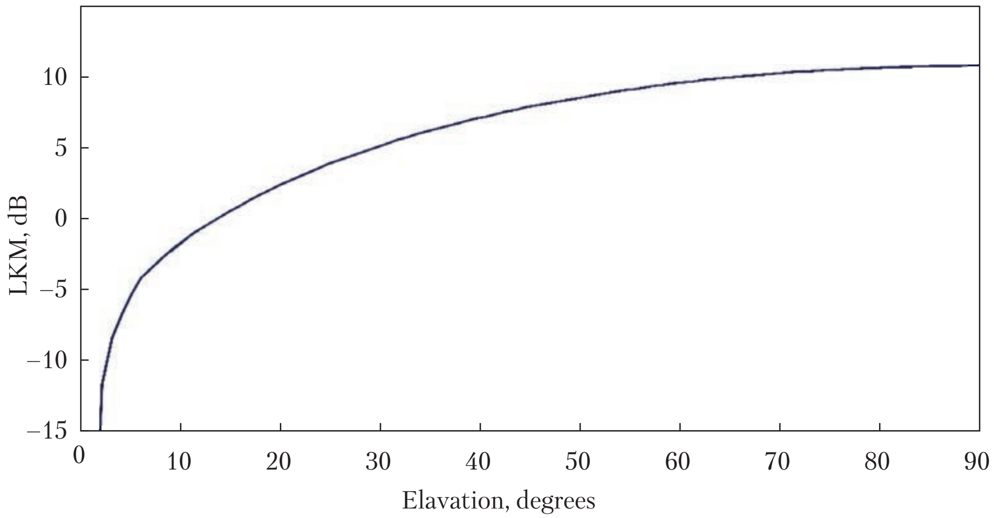

Fig. 5. Dependence of LKM on the satellite position angle (elevation) for MODCOD = 17 (16APSK 3/4)

The link margin of the communication channel "LEO satellite — earth station" was calculated depending on the MODCOD operating modes and the elevation angle value. The calculation results are presented in the form graphs (Fig. 3—7).

The calculation of the LKM of the Downlink X-band radio line for MODCOD = 1 (QPSK 1/4) is presented in Fig. 3. Dependence of LKM on the satellite position angle for MODCOD = 13 (8PSK 2/3) is shown in Fig. 4. The features of the LKM of the Downlink X-band radio link for 16APSK 3/4 and 16APSK 9/10 modulations are shown in Fig. 5 and Fig. 6. The calculation of the LKM of the Downlink X-band radio line for MODCOD = 28 (32APSK 9/10) is shown in Fig. 7. Dependence of the potential transmission

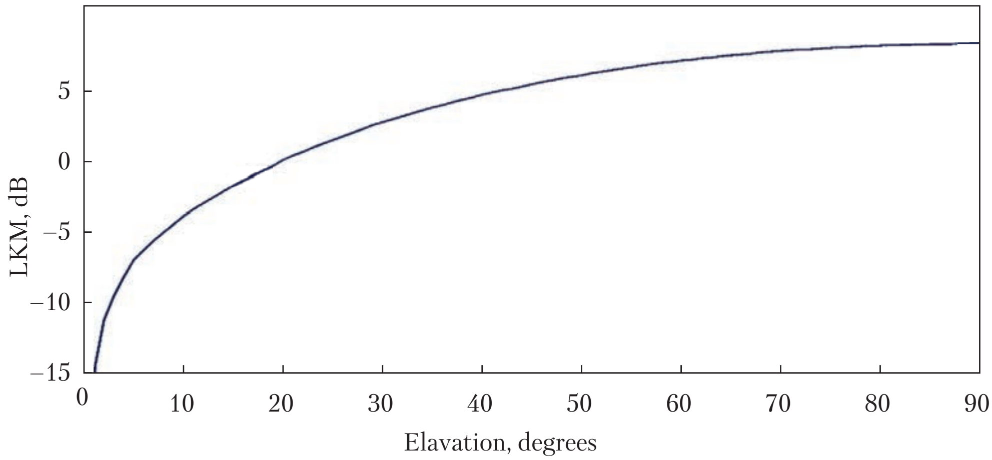

Fig. 6. Dependence of LKM on the satellite position angle (elevation) for MODCOD = 24 (16APSK 9/10)

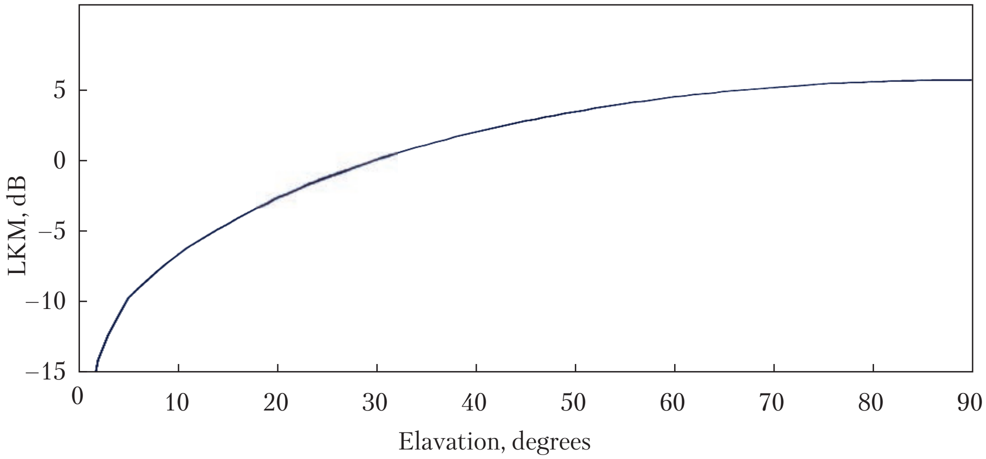

Fig. 7. Dependence of LKM on the satellite position angle (elevation) for MODCOD = 28 (32APSK 9/10)

rate on the satellite position angle (elevation) is shown in Fig. 8.

The calculation of the energy budget of the X-band downlink satellite radio line is implemented in the Excel program (Fig. 3—8). The conducted studies allow us to assess the possibility of using the DVB-S standard and frequency and polarization diversity for the needs of video information transmission from the EO satellite to the earth station.

As noted in [18], the proposed high-speed X-band transmitter allows for the implementation of a downlink payload with double polarization and three frequency channels per polarization. Each polarization has a special power amplifier, and each frequency channel has a special modulator. The X-band payload transmitter consists of a specified modulator (MODCOD), a high-frequency power amplifier, and a line-fed parabolic reflector or horn antenna. The conducted study corresponds to one channel, which is obtained by dividing the total output RF power of 1 W from the satellite power amplifier into three channels.

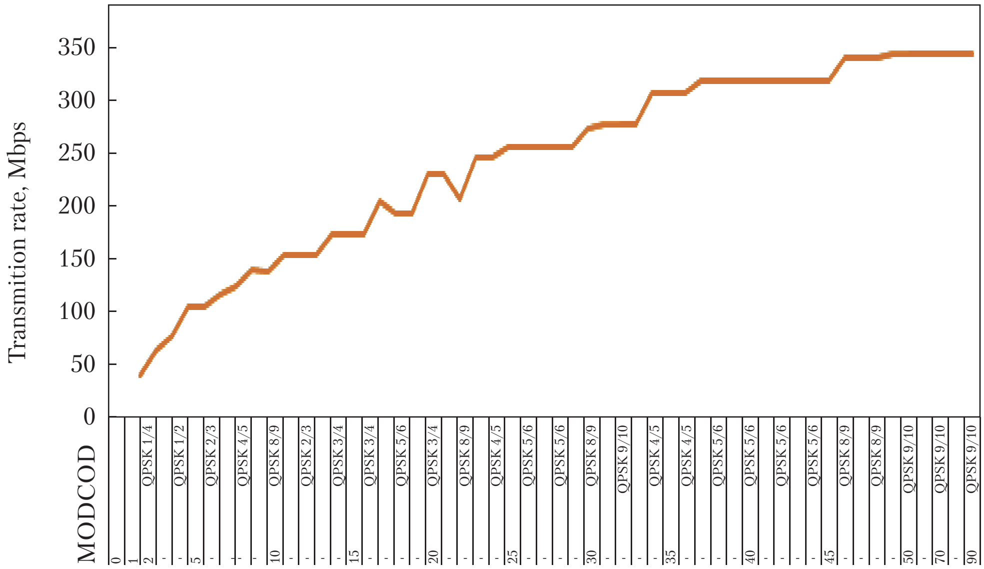

Fig. 8. Dependence of the potential transmission rate on the satellite position angle (elevation)

The results of the research (Fig. 3—8) show that at small values of the satellite position angle (that is, at a low height of the spacecraft above the horizon, elevation is equal 5 degrees) it is possible to establish communication at the smallest value of MODCOD = 1 with the QPSK mode 1/4, which provides a transmission speed of 38 Mbps (Fig. 3). Fig. 8 shows that the transition to higher MODCOD values is possible with an increase in the satellite position angle above the horizon. Only when the elevation value is 50 degrees, it is possible to use the faster MODCOD = 28 with the 32APSK 9/10 mode, which provides a transmission speed of 384 Mbps. The presented calculation results make it possible to assess the expediency of using this or that individual MODCOD and a certain satellite location angle for organizing the transmission of a large volume of video information (Fig. 8).

The paper proposes a methodology for calculating the link margin using the ACM function in DVB-S2 for additional adaptive modulation, coding (MODCOD) and power scheme at different positions of a small satellite with COTS components relative to the earth station, which allows determining the optimal location of the satellite for the full transmission of remote sensing video information Earth. It is shown that it is the DVB-S2(X) standard that makes it possible to organize a transmission channel of big data of video image data from the EO satellite to the ground station. On a concrete example of the implementation of a communication channel, it is shown that the DVB-S2(X) standard allows reducing the design budget of small satellites due to the use of integrated circuits presented on the telecommunications market and very cheap mass-market receivers.

During the development of the small satellite and during the subsequent calculation of the link margin, such advantages of the DVB-S2X standard were taken into account, such as: the use of multi-position modulation methods 64/128/256-APSK; use of improved algorithms of interference-resistant coding; using a rounding factor with smaller values; the use of improved filter schemes, which allow reducing gaps between carriers.

The application of the DVB-S2X standard allows approaching the Shannon limit due to the use of more efficient modulation and coding methods. For example, 16APSK modulation enables increasing channel bandwidth by 25% as compared with

8PSK modulation. However, even with DVB-S2X, it is not possible to fully reach the Shannon limit. This is because noise is always present in the communication channel, and its energy cannot be completely reduced to zero.

Thus, because of the conducted research, we can draw a general conclusion: the implementation of the proposed recommendations allows for the effective use of the satellite channel use of the satellite channel, ensuring more flexible and effective transmission of video data in various conditions. This allows increasing the amount of information transmitted during a communication session by choosing the optimal position of the satellite during a short communication session.

For the high-speed data transmitter proposed in [18], the downlink energy budget was calculated. Calculations of the link margin of the satellite-Earth radio link using various MODCOD modes were carried out. It was found that with an increase in the angle of the space station, a communication margin of 3 dB is achieved for various MODCODs, which leads to an increase in the speed of video information transmission.

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ПОКРАЩЕННЯ ЯКОСТІ ЗВ'ЯЗКУ В X-ДІАПАЗОНІ КАНАЛУ «СУПУТНИК LEO — НАЗЕМНА СТАНЦІЯ»

Вступ. Дистанційне зондування Землі суттєво сприяє розвитку багатьох галузей економіки нашої країни. Для вищої результативності технології важливо оптимізувати канал передачі відеоданих з точки зору визначення кута положення супутника.

Проблематика. Використання різних форм сигналів передбачає різні значення запасу каналу. З іншого боку, зміна кута спостереження супутника відносно наземної станції змінює довжину маршруту, яким проходить сигнал, і, відповідно, змінює енергетичні характеристики лінії зв'язку. Для малих супутників *CubeSat* з обмеженим запасом живлення можливість передачі інформаційного сигналу від супутника Землі до наземної станції стеження протягом короткого сеансу зв'язку, залежно від обраного режиму генерації сигналу, не була достатньо досліджена.

Мета. Удосконалення системи дистанційного зондування Землі.

Матеріали й методи. Теорія радіозв'язку в мікрохвильовому діапазоні, розрахунок запасу енергії лінії зв'язку при використанні функції *ACM* в *DVB-S2* для додаткової адаптивної модуляції, кодування (*MODCOD*) та схеми живлення при різних положеннях малого супутника відносно земної станції.

Результати. Розраховано запас енергії низхідного супутникового радіозв'язку, що дозволяє оцінити можливість використання стандарту *DVB-S2X* для потреб передачі відеоінформації із супутника дистанційного зондування Землі. Показано, що при малих значеннях кута положення супутника можливо встановити з'єднання в найнижчому режимі *QPSK* 1/4, що забезпечує швидкість передачі 38 Мбіт/с. Тільки коли кут положення супутника становить 50 градусів, можна використовувати швидший режим 32*APSK* 9/10, який забезпечує швидкість передачі 384 Мбіт/с.

Висновки. Використання стандарту *DVB-S2(X)* для малих супутників дозволяє ефективніше використовувати супутниковий канал, зокрема, забезпечує більш гнучку та ефективну передачу відеоданих для певних кутів спостереження супутників.

Ключові слова: супутниковий зв'язок, дистанційне зондування Землі, X-діапазон, DVB-S2X, енергетичний запас каналу.