Optoelectronics

Optical space communication. Review

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Abstract. Features of information exchange between satellites and satellites with ground stations and in the opposite direction are considered. The influence of such atmospheric factors as fog, rain, snow, atmospheric turbulence, background noise, and sky glow on the quality of information signals is analyzed. The expediency of using transmitter frequencies, which lie in the area of windows of the Earth transparency and are in the infrared region of the spectrum, has been established. In particular, generators of such frequencies in the near-infrared region can be InGaAs laser diodes, which are light in the region of about 1550 nm, and in the far-infrared region – cascade lasers, which are able to generate radiation in the range of 3.5 to 24 µm. InGaAs photodiodes and HgCdTe detectors should be used as receivers of the mentioned frequencies.

Keywords: air, space, satellite, communication, optical link.

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1. Introduction

Currently, communication with Earth's satellites in near and far space is carried out mainly by radio frequency methods, due to their following advantages [1–4]:

1. Opportunities to communicate anywhere in the world.
2. All satellite radio frequency communication networks are characterized by reliable and high-quality communication.
3. Large coverage area.
4. Relatively low-cost equipment and communication services.

At the same time, radiofrequency satellite communication has its drawbacks, among which there are the following ones [1–4].

1. Weak noise immunity. The huge distances between earth stations and the satellite cause a small signal-to-noise ratio on the receiver. To ensure a low probability of error in the exchange of information, you need to use large antennas, low-noise electronic components of devices, and complex noise-tolerant codes. This problem is especially acute in mobile communication systems, as they have limitations on antenna size and transmitter power.
2. The quality of satellite communication is significantly affected by the absorption of the radio signal by the atmosphere and the effect of signal fading, which is caused by the difference in the refractive indices of different layers of the atmosphere.
3. Influence of ionosphere effects, the cause of which is fluctuations in the distribution of free electrons. The result of their influence is the appearance of "flicker" signals, delayed propagation of signals, the appearance of variance, frequency changes, and rotation of the plane of polarization.
4. When located on the same line of the Sun, satellite, and ground station, the radio signal received by the ground station is distorted as a result of interference of electromagnetic waves of the transmitter and the Sun.
5. Usually satellites are located in inclined or polar orbits with an inclination of 86.5° and altitude of 780 km, because in this case it is required a low transmitter power and low cost of launching the satellite into orbit.

The presence of these shortcomings encourages scientists to look for other methods of communication with satellites. One of the most researched alternative methods today is the optical method of information exchange. The purpose of this work is to analyze the features of optical space communication.

2. Optical space communication

Currently, optical communication methods are becoming widespread due to the following advantages over radio-frequency methods [5–7]:

- insensitivity to external electromagnetic fields and temperature fluctuations;
- no short circuits;
- smaller dimensions and weight in comparison with copper wires used in the implementation of radio-frequency communication methods;
- less transmitter power;
- high bandwidth (more than 30 Gbps);
- high value of the quality indicator (1 GHz (km));
- no need to license the radio-frequency spectrum, because for the latter interference from a neighboring carrier is the main problem due to spectrum congestion. Therefore, solving this problem requires licensing of spectrum by regulators;
- easy installation and maintenance, lower cost and deployment time communication systems;
- high security of information in optical communication, because optical information cannot be detected by spectral analyzers;
- due to the high directivity of the very narrow optical beam, which complicates interception of optical signals.

At the same time, optical communication has inherent shortcomings, among which there are the following ones [5]:

- rigid system of automatic adjustment of communication due to narrow beam divergence;
- dependence of optical communication on atmospheric conditions that can impair communication;
- dependence of the connection on the position of the Sun relative to the laser transmitter and the receiver, as additional irradiation of the receiver with sunlight may be accompanied by distortion of optical information.

Modern systems for transmitting information over optical channels consist of three main components: transmitter, optical channel, and receiver.

The transmitter converts an analog or digital electrical signal into a corresponding light signal and sends it to the channel through which the signal is transmitted to the destination, which is the receiver. The receiver reproduces the message transmitted *via* the optical channel into an electrical signal. In fact, the optical channel defines the properties of the transmitter and receiver. Typically, the signal transmitted from the spacecraft is transmitted to stations that are located on the Earth's surface, where the received information is processed. The requirements for the transmitter and receiver largely depend on the distance of the spacecraft from the Earth surface.

It is known [8] that our planet is surrounded by a gas shell, which is usually called the atmosphere and extends to a distance of about 1000 km from the Earth surface. Three-quarters of the mass of air is contained in the layer about 11 km thick from the Earth surface. With increasing the altitude from the Earth surface, the atmosphere becomes more sparse, and without a certain boundary between the atmosphere and outer space. The Pocket Line, located 100 km from the surface, is often considered as the boundary between the atmosphere and outer space.

Today, a large number of satellites rotate in the upper atmosphere, moving in the following orbits around the Earth [9]: geo-stationary Earth orbit (GEO), medium Earth orbit (MEO), low Earth orbit (LEO), and highly elliptical orbit (HEO).

Geo-stationary Earth orbit

The orbits of GEO satellites are located at the altitude close to 35,900 km. These satellites move in a circular orbit at the speed close to 3075 m/s, so for the terrestrial observer, the position of the satellite remains constant.

Advantages of geo-stationary Earth orbit

1. It is possible to cover almost all parts of the Earth with just 3 GEO satellites.
2. Antennas need not be adjusted every now and then but can be fixed permanently.
3. The lifetime of a GEO satellite is rather high, usually around 15 years.

Disadvantages of geo-stationary Earth orbit

1. Larger antennas are required for northern/southern regions of the Earth.
2. High buildings in a city limit the transmission quality.
3. High transmission power is required.
4. These satellites cannot be used for small mobile phones.
5. Fixing the satellite at geo-stationary orbit is very expensive.
6. The presence of a significant delay in signal transmission (up to 250 ms).
7. The presence of the influence of solar interference on the quality of information.

Medium Earth orbit

Satellite at different orbits operates at different heights. The MEO satellite operates at about 5000 to 12000 km away from the Earth surface. These orbits have a moderate number of satellites.

Advantages of the medium Earth orbit:

1. Compared to LEO system, MEO requires only a dozen satellites.
2. Simple in design.
3. Ability to transfer controlling the satellite from one scientific measuring point to another without disruption or loss of satellite service

Disadvantages of medium Earth orbit

1. Satellites require higher transmission power.
2. Special antennas are required.

Low Earth orbit

LEO satellites operate at the distances within the range 500…1500 km.

Advantages of low Earth orbit

1. The antennas can have a low transmission power close to 1 W.
2. The delay of packets is relatively low.
3. Useful for smaller foot prints.

Disadvantages of low Earth orbit

1. If global coverage is required, it requires at least 50 to 200 satellites in this orbit.
2. Requires special mechanisms to transfer control of the satellite from one scientific measuring point to another without disruption and loss of service for some time.
3. These satellites involve complex design.
4. Very short lifetime of 5…8 years. It is assumed to use 48 satellites with the lifetime of 8 years each, a new satellite is needed every 2 months.
5. Data packets should be routed from satellite to satellite.

Highly elliptical orbit

There are very few satellites in this orbit.

Communication in space

The lines of communication between spacecraft that study the planets of the solar system and with Earth stations need to be considered separately. This type of research includes missions to the Sun [10], Moon [11], Mars [12], and others.

Regardless of where the satellites are located, they can exchange information with each other and with ground stations. When exchanging information between satellites, the atmospheric effects become noticeable when spacecraft are at orbits close to 120 km, and when exchanging information with ground stations, the quality of communication is always affected by the atmosphere. Its minimal impact will be provided, if the signal transmission is carried out at the wavelengths lying in the area of the windows of the atmosphere (Fig. 1) [8]. The fragmented part of the transmission spectrum indicates the presence of "windows" in the visible and near-infrared ranges, namely between 0.2 and 5 µm (Fig. 2) and in the infrared range, namely between 8 and 13.4 µm.

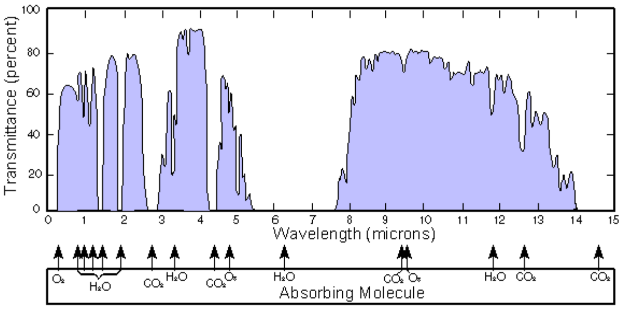

Fig. 1 The transmission spectrum of solar radiation through the Earth atmosphere at various wavelengths in the visible and infrared spectral ranges [8].

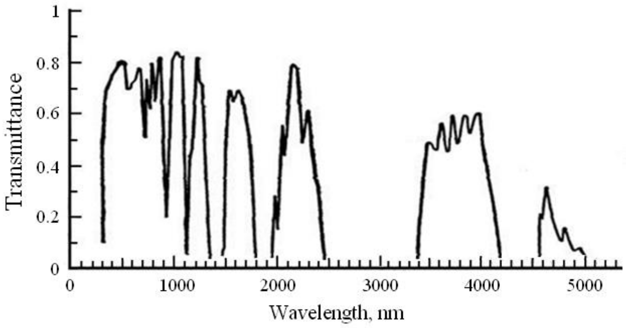

Fig. 2. Transmission of the Earth atmosphere in the visible and near-infrared parts of the spectrum, *i.e.*, within the spectral range from 300 up to 5200 nm [13].

Radiation with the wavelengths from the "windows" can be used to communicate between satellites and ground stations.

The presence of satellites in the Earth orbits allows one to provide the following services:

1. Establishing Internet and mail connection. Transmission of television and telephone information.
2. Remote sensing of the Earth surface and observation of terrestrial objects.
3. Meteorological programs, such as the study of different layers of the atmosphere and the determination of ozone in the atmosphere.
4. Military programs, such as communication between military units located nearby, studying the location of the enemy, *etc*.

The following atmospheric factors influence on the quality of these services:

- extinction of radiation related with molecular absorption in the atmosphere at a given wavelength (see Figs 1–3);

- extinction of radiation related with its scattering by molecules (Rayleigh scattering) and by aerosol particles (aerosol scattering);

- scattering of light by atmospheric particles, for example, on water drops or snowflakes;

- change in the refractive index of the air, which is caused by the change in the temperature of the atmospheric air and accompanied by the refraction of the light flux, especially when the temperature gradient is large.

The main advantage of optical communication over radiofrequency is the security of information transmission [14] because the directional pattern of the laser flux is narrow and the laser beam itself cannot be detected by radio-engineering methods. Other advantages of optical communication are as follows:

1) The cost of using optical satellite communication does not increase with the number of users and does not depend on the distance between the points of reception and transmission of signals.

2) Satellite communication covers all terrestrial users, even those in rural and remote areas of the world, as well as maritime and air navigation facilities.

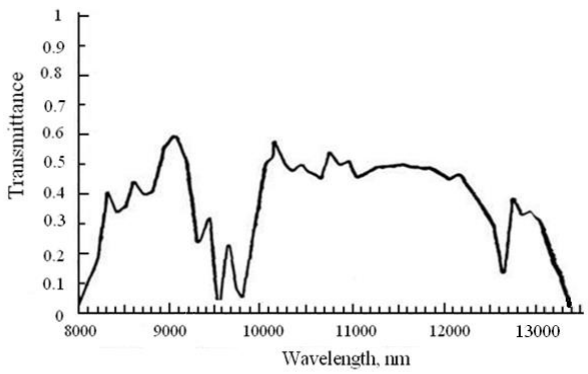

Fig. 3. Transmission of the atmosphere in the infrared part of the spectrum within the range 8000…13400 nm [13].

3) Satellites are broadcast media, as the transmitting antenna can be designed to send signals to service areas, both small and large cities in the country.

4) Earth observation satellites can track ocean and air currents, as well as the scale of major fires, oil spills, and air pollution; besides, this information helps to organize emergencies and monitor the state of the environment.

5) Satellite communication can be provided between many stations, while terrestrial communication enables communication only between two stations.

6) Relatively fast installation. As soon as the satellite is in the appropriate position in orbit, the desired earth station is deployed for communication in days or hours.

7) The cost of a satellite does not depend on the distance to which it sends signals, while the cost of the terrestrial network is proportional to the distance.

8) The satellite itself serves as a repeater. For terrestrial communication, the antennas are positioned at a certain height to overcome interference.

9) Satellite systems provide communication between remote areas (hilly areas, islands, *etc*.), *i.e*., where the terrestrial system is unable to support reliable communication.

10) Production of a satellite is expensive, but after that, it will work for years, because their operating cost is low.

11) The signal quality does not depend on the distance, until the signals from two satellites sent at the same wavelength overlap.

Disadvantages of satellite communication:

1. If the satellite is located at a distance of 75000 km from the Earth surface, the delay between transmission and reception of the signal reaches ¼ s, which reduces the efficiency of data transmission.

2. Due to the low gain of the antenna, the bandwidth of the communication channel is overflowed.

3. The presence of large atmospheric losses limits the carrier frequency to 30 GHz.

4. The signal loss is inversely proportional to the square of the distance traveled and inversely proportional to the square of the frequency used. That is, as the distance doubles, the power obtained decreases four times. Similarly, as the frequency doubles, the obtained power decreases four-fold. The loss of the optical signal as it propagates through the Earth atmosphere for geostationary satellites ranges from 190 up to 210 dB, depending on the frequency used.

5. The presence of molecules and aerosols in the atmosphere is the reason for formation of transparency windows (Figs1 to 3). The wavelengths that fall into the area of the transparency windows can be used to communicate between satellites and ground stations. The following atmospheric factors must be taken into account [15–17]: absorption of radiation at a given wavelength caused by the unequal transmission of the atmosphere (see Figs 1–3); extinction of radiation, which is related with scattering by molecules (Rayleigh scattering) and aerosol particles (aerosol scattering).

It is also necessary to take into account absorption and scattering caused by fog, rain, snow, atmospheric turbulence, light flux divergence [15–17].

Fog. Small drops of water that condense in cold air from water vapor, form a mist. When light propagates in a fog, both light absorption and scattering occur. During heavy fog, when the visibility is even less than 50 m, the attenuation can be more than 350 dB/km.

Rain. The rain does not affect transmission of the optical signal as much as in the fog. Rain is formed by water droplets ranging in size from 100 to 10,000 μm. The loss of light attenuation during the transition from weak rain (2.5 mm/h) to heavy rain (25 mm/h) is from 1 to 10 dB/km for the wavelengths within the range 850 to 1500 nm.

Snow. The size of the snow particles lies between the fog and raindrops. Therefore, attenuation of optical signals by snow is higher than by rain, but lower as compared to fog. During heavy snowfalls, the path of the laser beam is blocked by increasing the density of snowflakes or by forming the ice on windows of the panels. In this case, its attenuation can be compared with fog and ranges from 30 to 350 dB/km, and it can significantly reduce the availability of an FSO communication (decrypt) system.

Atmospheric turbulence. Atmospheric turbulence is a phenomenon caused by variations in temperature and atmospheric pressure along the path of light propagation. It is the change in temperature and atmospheric pressure that leads to formation of turbulent vortices of different magnitudes and different refractive indices. These vortices act as prisms or lenses and ultimately cause a destructive effect on propagation of the light beam. As a result, it leads to an increase in the cross-section of the sunlight flux.

The losses caused by the divergence of the beam. Propagation of optical light flux in the atmosphere is accompanied by its diffraction difference, *i.e*., an increase in the cross-section of the light flux with increasing the distance from the transmitter. Since the geometric dimensions of receiver are limited, the presence of diffraction differences is the cause of geometric losses, the magnitude of which increases with increasing the distance between the transmitter and receiver.

Background noise and radiance of the sky. The sources of background noise are: (i) light scattered in the atmosphere, (ii) light from the Sun, and other stellar objects. Reducing the effect of background noise is achieved by installing an optical filter at the input of the receiver with a narrow spectral band for the wavelength of the transmitter.

Transmitter. The main function of the transmitter is to transmit data through free space to a particular receiver. Typically, the transmitter consists of an optical source, modulator and optical system for generating the light flux [17, 18].

The light source can be either semiconductor or solid-state laser or LED. The choice of light source for the transmitter depends on the following factors [17, 18]: wavelength, the choice of which is largely defined by the window of transparency of the Earth atmosphere, the power of the radiation pulse, the ability to modulate the flow of light, service life, eye safety, beam size and angle of divergence, physical size, and price.

The wavelength of radiation is defined by the lowest value of absorption in the window of transparency of the Earth atmosphere (Figs 1 to 3). Transmitters that generate light in the visible or near-infrared regions of the spectrum are used experimentally (see Table 1). Emitters with these wavelengths were chosen because of the availability of transmitter and receiver components for these wavelengths.

Therefore, in the visible and near-infrared regions, the light sources are laser diodes (LD). They are characterized by stability, very low threshold currents, simple signal modulation requirements, and good beam quality. GaAs/AlGaAs lasers are mainly used to emit light within the range 750…980 nm.

In the infrared part of the spectrum in the Earth atmosphere, there is a window with a small value of absorption. This window is located in the spectral region of 8…13.4 μm (Fig. 3). The source capable to emit within this range can be the CO_2 laser. This type of laser requires complex power supply, its dimensions are large, it is heavy and expensive [19]. Quantum cascade lasers (QCL) are more promising for the mentioned spectral region [19, 20]. They are used as sources of infrared radiation (λ = 3.5…24 μm) based on a unipolar generation mechanism; QCLs have unique high-frequency characteristics with a theoretical bandwidth of over 100 GHz [19]. Information on industrial efficiency is contained in [21, 22].

When choosing a light source, one needs to consider the risk of damage to the retina by laser light. The most dangerous are sources that emit light in the visible and near-infrared regions of the spectrum. Laser light from the infrared region is absorbed by the front of the eye, before the energy is focused on the retina. The absorption coefficient in the anterior part of the eye is much higher for long wavelengths (>1400 nm) [18]. For this reason, the allowable transmission power for the lasers operating at 1550 nm is higher, and they are used to transmit information over long distances.

There are two types of modulation of laser radiation – internal and external. During internal modulation, the parameters of the laser change either by controlling the supply current or by changing the quality factor of the resonator. With external modulation, light flux control is achieved by changing either the amplitude or polarization, or phase of the light flux. Regardless of the modulation method, the signal amplitude often changes.

Table 1. Light sources applied in selected FSO systems [17].

Laser	Wavelength, nm	Laser/LED power	Beam divergence	Application
Matrics LEDs	450	6 W	180°	Underwater communication
Nd:YAG	532	250 mJ 12 ns	110 μrad	Deep space mission
LD	532/486	5 W	180°	Underwater communication
LD	785	25 mW	1 mrad	Ethernet
AlGaAs	830	60 mW	6 μrad	Inter-satellite communication
Argon-ion/GaAs	830	13 W	20 μrad	Ground-to-satellite link
VCSEL	850	9 mW	3.5 mrad	Last mile link
LED	800−900	bd	17 mrad	Communication between buildings
LD	1550	113 mW	50 mrad	UAV-to-UAV link, L = 2 km
LD	1550	200 mW	19.5 μrad	Ground-to-UAV link
QCL	8400	740 mW (100 ns, f = 1 MHz)	2 mrad	Laboratory FSO link (IOE MUT)

The presence of the signal corresponds to unity. Its absence – to zero. That is, all information is transmitted by a binary system [18]. A change in pulse width is often used to modulate the signal. In this case, the pulse of large width corresponds to unity, the pulse of small width – to zero.

The spherical-cylindrical lens placed at the output of the transmitter forms a laser beam with a Gaussian distribution of light along the cross-section and a minimum difference in the flux of laser light.

The receiver usually consists of a telescope or lens, optical filter, photodetector, amplifier, and demodulator for proper reception of the information signal [17, 18].

The size of the beam on the surface of the receiver depends on the difference between the beam and the transmission range. Typically, the divergence of the beam generated by the transmitter lies within the range 1 to 8 mrad. To ensure the desired intensity at the input of the photodetector, they set a telescope in front of it. The telescope collects and focuses optical radiation on the active area of the photodetector. A filter in front of the photodetector reduces background radiation (such as sunlight). The photodetector converts the energy of photons into an electrical signal. It provides a high response to the desired wavelength, low noise, sufficient dynamic range, and signal bandwidth. The most common photodetectors are PIN photodiodes and avalanche photodiodes. The output signal of photodetector is enhanced by the amplifier. When transmitting information by radiation at wavelengths of the visible or near-infrared ranges, its detection of photons can be performed by Si, InGaAs and, Ge photodetectors [18]. In particular, the maximum sensitivity of the Si photodetector is in the vicinity of 850 nm, InGaAs – in the vicinity of 1550 nm. Ge photodetectors are rarely used because of the high level of dark current. HgCdTe detectors are mainly used to detect photons generated in the middle (3…5 μm) and long-wavelength (8…14 μm) spectral regions [23]. The main advantage of HgCdTe as a material for the manufacture of detectors is its following properties [24]:

- Adjustable bandgap from 0.7 to 25 μm.
- Direct width of the restricted area with a high absorption coefficient.
- Moderate dielectric constant/refractive index.
- Moderate thermal expansion coefficient.
- Availability of substrates with a large bandgap and consistent with the lattice constant of the substrate and HgCdTe.

The main disadvantage of HgCdTe detectors is the need to cool them to cryogenic temperatures. Temperatures well below 300 K (usually 80…200 K) are required to obtain high-efficiency detectors. Cooling requirements can significantly increase the cost and size of IR systems, so one of the main goals of the study is to increase the operating temperature of photodetectors. This can be achieved as follows: use Peltier elements to cool the detector or technically implement cascade uncooled detectors type based on InAs/GaSb.

A typical cascade uncooled InAs/GaSb detector has the following technical parameters [25]: cut-off wavelength close to 8 μm, specific detection ability $D^* = 1 \cdot 10^9\ \mathrm{cm}^{1/2}\mathrm{W}^{-1}$, bandwidth 155 Mbit/s, response time approximately 100 ns, data transfer rate up to 10 Mbit/s.

To determine the prospects of InAs/GaSb detectors for registration of infrared photons, the properties of HgCdTe and cascade InAs/GaSb detectors were compared in [26] (Table 2).

According to Table 2, parameters of commercial HgCdTe detectors are slightly better than those of InAs/GaSb detectors. However, with account of the shorter development time inherent to InAs/GaSb photodetectors, as compared with many years of researching the HgCdTe photodetectors, the prospects of the former are quite high. With further optimization of the doping and cascade design of InAs/GaSb, a further increase in the efficiency and operating temperature of these photodetectors is expected.

Table 2. Specifications of the two IR detector modules based on an MCT detector and an InAs/GaSb T2SL detector, respectively.

	MCT	InAs/GaSb T2SL
Detectivity	$6.8 \cdot 10^8\ \mathrm{cm}\sqrt{\mathrm{Hz}}/\mathrm{W}$	$6.7 \cdot 10^9\ \mathrm{cm}\sqrt{\mathrm{Hz}}/\mathrm{W}$
Bandwidth	100 MHz	10 MHz
Cutoff wavelength	10.6 μm	9.3 μm
Operating temperature	226 K (2-stage TEC)	200 K (4-stage TEC)
Operation mode	photovoltaic	photoconductive
Opening area	1×1mm	0.5×0.5mm
Lens	hemispheric	hyper hemispheric

3. Conclusion

Currently, the exchange of information between satellites and these with ground stations is mainly carried out by radio-frequency methods. Optical methods can compete with this type of communication due to higher data rates; easy and fast deployment of transmitters and receivers; less weight of the satellite; less power required to power satellite elements; no need to license spectral frequencies. It is better to use optical communication to exchange information between spacecraft operating in outer space and transmit information to receiving stations in a highly elliptical orbit, where the effects of atmospheric phenomena on the propagation of optical signals are minimal. In this case, for this orbit, one needs to create a sensor network consisting of a set of small satellites that will perform coordinated measurements of optical signals and transmit them to ground stations. The widespread implementation of optical communication in space at infrared wavelengths is expected after the technical development of highly sensitive, reliable photodetectors capable to operate at room temperatures. However, the main obstacle to the widespread use of optical communication between certain objects on Earth and in outer space is the presence of extinction of the optical signal by the Earth atmosphere caused by fog, snow, rain, aerosols, turbulence, *etc*. In the presence of atmospheric factors, the exchange of information through optical channels between users is limited to hundreds of meters.

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Оптичний космічний зв'язок. Огляд

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Анотація. Розглянуто особливості обміну інформацією між супутниками і супутниками з наземними станціями та у зворотному напрямку. Проаналізовано вплив на якість інформаційних сигналів таких атмосферних факторів, як туман, дощ, сніг, турбулентність атмосфери, фоновий шум, світіння неба. Встановлено доцільність використання частот передавача, які лежать в області вікон прозорості Землі та знаходяться в інфрачервоній області спектра. Зокрема, генераторами таких частот у ближній інфрачервоній області можуть бути лазерні діоди InGaAs, які випромінюють в області близько 1550 нм, а в дальній інфрачервоній області – каскадні лазери, здатні генерувати випромінювання в діапазоні від 3,5 до 24 мкм. Як приймачі зазначених частот слід використовувати фотодіоди InGaAs та детектори HgCdTe.

Ключові слова: повітря, космос, супутник, зв'язок, оптичний зв'язок.