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AIR-TO-GROUND TRANSPORT NETWORKS BASED ON LASER COMMUNICATION

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Annotation. Organization of mobile Internet on board of the aircraft is examined. Various ways of a "ground – aircraft" transport channel formation are analyzed and the use of laser communication in this capacity is proposed.

Introduction. Every year, mobile internet on board an aircraft becomes an urgent need, and in recent years, the situation with internet access on board an aircraft has improved significantly, despite the high cost and slowness of downloads. Many airlines provide access to the Internet on board at a very affordable tariff scale, while the options change dynamically and become more flexible, and some airlines even offer free of charge and for everyone to attract customers. This is due to the fact that organizing Wi-Fi on board of an aircraft is difficult and expensive. The main problem is the organization of the transport channel "land - aircraft".

Formulation of the problem. There are two systems that provide the connection of the World Wide Web on board an airliner. One of them is called "Air-to-Ground (ATG)", it involves the transfer of data "from air to ground" [3].
On the ground, there are base stations of cellular operators whose antennas are directed downwards; it is enough to provide additional antennas installed on the same towers, but directed upwards. In turn, it is necessary to place antennas on the bottom of the aircraft, and inside to provide a modem with special programs that allow communication with the airliner. An experimental Air-to-Ground system called DA2GC [1] is shown in Fig.1.

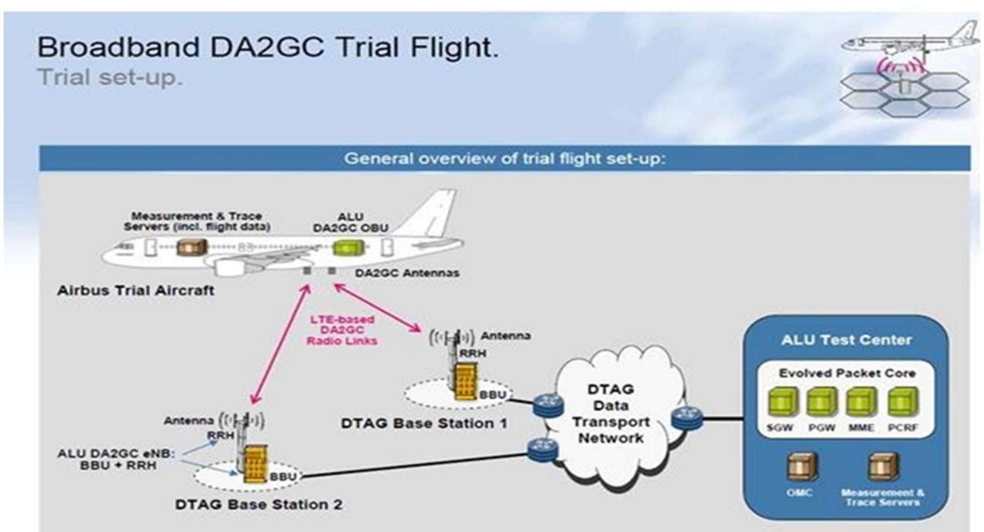

Fig.1 DA2GC system structure

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The principle of data transmission is similar to cellular communication, i.e. the base station transmits a signal to the aircraft, which acts as a flying 3G router. A number of BTSs are located along the route of the aircraft, and several stations are connected to the aircraft at once and in automatic mode. Switching occurs at the moment when the liner leaves the airspace of one BTS and enters the coverage area of another, i.e. handover occur.

A similar technology for providing Internet access to aircraft is widely used today. However, it is impossible to connect the Internet signal to a mobile phone or any other gadget, since a special program installed on board the aircraft is an "intermediary" signal transmission.

This CDMA EV-DO technology is already in use in the US and Canada in the 800 MHz band and is currently being developed further in the 2.3 GHz band. To cover the territories of the USA and Canada, it turns out that about 200 such stations are enough, which provide an Internet connection speed of up to 9.6 Mbit per second [2].

China is also testing the possibility of applying the LTE TDD standard in the 1800 MHz band. A test network was built using 17 base stations by the China Telecom operator on the Beijing-Chengdu line.

DA2GC systems provide broadband services on board aircraft, including the Internet. Transport communication channels are organized through radio links between the aircraft and the network of ground base stations (Fig. 1). One base station is enough to cover about 100 square meters. km. Stations are established on the basis of routes and airways and there is no need for continuous coverage.

The advantages of the DA2GC system are:

- deployed in a short time and relatively low equipment cost;
- has a low signal delay time;
- relatively low cost of providing the service.

A significant disadvantage of the ATG-based system is the ability to install and mount base stations only on the ground, i.e. when passing the airspace over the ocean or sea, the system will not work.

In Europe, the choice of frequency band for DA2GC systems has not yet been finalized. The communications administrations of the CIS countries, as well as Russia, are pursuing a policy of harmonizing the use of the radio frequency spectrum with European countries, therefore, the introduction of the DA2GC communication system on the aircraft of these countries should be considered relevant.

Initially, about 10 frequency bands were offered for DA2GC systems ranging from 790 MHz to 6 GHz. CEPT is currently considering two bands for use in DA2GC systems:

- 1900 -1920/2010 - 2025 MHz - frequency plans 2x10 MHz (FDD) or 1x20 MHz (TDD);
- 5855 - 5875 MHz (frequency plan 1x20 MHz (TDD).

CEPT believes that no more than two DA2GC systems can be deployed, one in each of the frequency bands, and commercial deployment began in 2017.

Due to the inability of the ATG-based system to operate when the airspace passes over the ocean or sea, satellite communications have been proposed. The principle of operation of satellite communications is the use of repeater satellites in geostationary orbit, allowing communication with aircraft and ground base stations. The coverage area of such systems can be different, on average it is hundreds of thousands of square kilometers (Fig. 2) [2,4].

Fig. 2 Scheme of the Internet in an airplane via satellite

The signal strength is determined by the frequency used and the size of the antennas at the stations. Modern such satellite communication can provide about 50-100 Mbit per second in the transport channel, which will be distributed on the aircraft between subscribers. Obviously than more subscribers will be connected to the Internet, the slower will be the speed. It is noted that this speed is only enough for visiting social networks or browsing the web, and it is impossible to watch anything online.
To organize satellite transport channels, it is necessary to install very heavy and large special antenna installations on an aircraft, which negatively affect the aerodynamic characteristics of an airliner. Fuel consumption increases and as a result the cost of a flight on such aircraft with the Internet will be much more expensive than on liners that do not have access to the World Wide Web [5-7].

It is also possible to use relay satellites on low orbits, particularly the Starlink system. Following the request of SpaceX to the FCC dated April 16, 2021, for different options of placing a terminal on moving objects, ITU allocated a certain frequency range in the Ku band with a total width of 200 MHz for the service [22]. The American aerospace company Space Exploration Technologies Corp (SpaceX) has received permission from the US regulator to connect several vehicles, including aircraft and naval vessels, to the Starlink satellite Internet [23]. Terminals other than ordinary civic terminals will be used for installation on airplanes,

ships and heavy-duty vehicles. These terminals will have to withstand heavy physical exertion and be better protected from environmental impact.
SpaceX has already launched a satellite Internet service on airplanes. Testing conducted on the aircraft of the regional airline JSX showed the data transfer rate of about 100 Mbit/s [22]. At the same time, the description of the service says that Starlink Aviation plans to provide speeds up to 350 megabits per second with low latency on board of the aircraft by 2023. However, due to the lack of inter- satellite communication channels (ISL - Inter Satellite Link) in Starlink, it is not possible to provide services in seas and oceans, except at a short distance from the coastline. This is due to the installation of gateways with connected fiber-optic cable for Internet access only on land [24]. A set, consisting of a terminal and access points, is estimated at approximately $150,000US and the subscription fee will be from $12,500US to $25,000US per month. Also, during the booking process, the company evaluates the package for $ 5,000. Of course, the expected 350 megabits per second are neither 10 megabits nor comfortable. Additionally, the price is quite high and it is not known how it will change in the future.
When implementing ISL in Starlink, in addition to technical and economic problems, there will also be another problem related to the ability of a network subscriber to access the Internet from another country or transmit information from one terminal to another, bypassing any terrestrial communication nodes. However, almost all, especially the developed countries, have legislations that oblige all telecom operators to ensure that special investigation services can access the traffic transmitted in their networks, more specifically guaranteeing access. Whether the secret/special investigation services will read the correspondence or not will be a matter of a court and other legislations. But telecom operators MUST PROVIDE ACCESS.
It follows from the foregoing that the main problem in organizing communication between the aircraft and the Earth is the organization of the transport channel "Earth - aircraft". Currently, this problem is solved by using ATG systems and satellite communications. However, both systems do not provide the connection of the World Wide Web to the board of the airliner at the speed required for the comfortable work of subscribers. To master even higher information transfer rates, it is necessary to switch from radio to laser information transmission systems [8–13].

Solution. Laser communication is similar to Open Optical Transmission Systems (OOTS) or, in English, Free Spact Optics (FSO), which came into use in the late 90s as a result of the combination of telecommunications and laser technologies. With the creation in 1998 of inexpensive semiconductor lasers with a power of more than 100 mW, as well as the use of digital signal processing to combat non-normalized signal attenuation, FSO began to be widely used in telecommunication systems. They work in the infrared range of the spectrum, the operating wavelengths are usually in the range of 810 - 910 nm.
In laser communication, as well as in FSO, the atmosphere is used for the propagation of electromagnetic waves and therefore the availability of the communication channel is determined by its state. At the same time, practice shows that such atmospheric phenomena as rain, snow and fog do not completely disrupt the operation of the system. Modern FSO, with

the right approach and compliance with operational requirements, provide an availability of about 99.9%, with error rates of no more than 10-12. FSO work within the line of sight, the distance is usually several kilometers. In the case of installing transmitters on hills, the interval can be tens of kilometers, and in the mountains, hundreds of kilometers.

Space laser communication lines also consist of an interface module, a modulator, a laser, an optical transmission system, a demodulator, and a receiver interface module. The receiver usually consists of a fast pin photodiode or an avalanche photodiode. The main differences between the FSO and the space communication line is that in the first case the laser beam propagates horizontally to the ground, and in the second case it propagates vertically [14].

A laser beam in a space communication line crosses the atmosphere in the vertical direction and is mainly affected by the densest lower layers of the atmosphere with a thickness of several kilometers. In FSO, the beam propagates horizontally, through the most disturbed ground layers of air, and this has a significantly greater effect on it.

For successful transmission of information by an open laser beam, as mentioned above, it is necessary to take into account the dependence of the transmission of optical radiation on the state of the air. Therefore, comprehensive studies of the propagation of laser radiation in the atmosphere were carried out, allowing users to evaluate the capabilities of these lines in specific weather conditions [18].

The propagation of laser radiation in the atmosphere is accompanied by a number of phenomena of linear and nonlinear interaction of light with the medium. However, none of these phenomena appear in isolation. According to purely qualitative features, these phenomena can be divided into three main groups: absorption and scattering by air gas molecules, attenuation by aerosols (dust, rain, snow, fog), and radiation fluctuations by atmospheric turbulences.

The atmosphere is a mechanical mixture of gases, vapors, liquid droplets and solid particles. It always contains variable amounts of dust, smoke, ice crystals. Therefore, the atmosphere is an aerosol whose composition is continuously changing due to mixing. Speaking of aerosol scattering in general, they mean aerosol attenuation due not only to scattering, but also to the absorption of radiation by aerosol particles. All types of atmospheric aerosols can be grouped into the following main classes: clouds, fogs, hazes, frost and precipitation - rain or snow. In clouds and fogs, the most probable particle radius is 5–6 μm, and in haze it is 1–2 orders of magnitude smaller. Therefore, the attenuation of micron radiation in hazes is lower [18].

One of the main tasks in the design of laser communication systems is to determine the transparency of the atmosphere, which can be solved by collecting and processing statistical data for the corresponding geographical region (GR) [16,17,19].

The next difference between the space link is the significantly greater distance between the transmitter and receiver than in the FSO. The spacecraft located in geostationary orbit is located at a distance of about 36 thousand km from the Earth. At such distances, the divergence of the laser beam becomes significant. For example, a radiator with an aperture of 20-30 cm in the optical system, at a wavelength of 900 nm, will provide a divergence angle of about 1 arc second, which will create a light spot on the earth's surface 200 m in size and the signal near the earth's surface will be greatly weakened. In this case, stable operation of the receiving device will be possible with an optical system aperture diameter of about 60–80 cm.

In terms of bandwidth, laser optical channels are comparable to wired fiber optic lines, in particular, the developers claim a data transfer rate of 10 Gbps, with a range of up to 100 km. [15]. It should also be noted that if diffraction quality is required for an optical emitter, then the optical receiving system can be much simpler, you can use the simplest ones (amateur telescopes).

The introduction of laser technologies with such speeds in the transport channels "Earth - Aircraft" will provide each passenger in each of the aircraft with real broadband mobile Internet at an affordable price, i.e. you can even watch HD video or play online games, but such a connection is needed not only for entertainment. For example, it will allow real-time collection of data from all aircraft systems and send them to the ground for analysis in order to predict failures, i.e. if at present these data are stored by flight recorders and analyzed only after a disaster, then in the future it will be possible to prevent these disasters. In addition, in real time it will be possible to broadcast the image from the cameras to the ground, so the situation with the Malaysian Boeing (MH370), which was simply “lost”, will certainly not be repeated.

Space laser systems have already been tested and operate in satellite-to- ground, satellite-to-aircraft and satellite-to-satellite modes in the US and Europe. Tests and systems operating in the Earth-aircraft and aircraft-Earth modes have not yet been published in the open press, but judging by the operating systems, they will also work successfully [14].

The problem of cloudiness can be solved by terrestrial methods; for this, several points should be selected on the Earth's surface that satisfy the following conditions:

- a large number of clear days and nights in each of the locations, or whatever approximately equivalent, low percentage of cloud cover;
- remoteness of points up to 400 km from each other in order to local weather conditions in these places did not correlate with each other;
- Proximity or connectivity to high-speed terrestrial optical channels of information transmission.

Such a construction of the organization of transport communication channels will allow, in case of dense cloudiness in the area of an active base station, to switch to another base station, over which there are no clouds (Fig. 3).

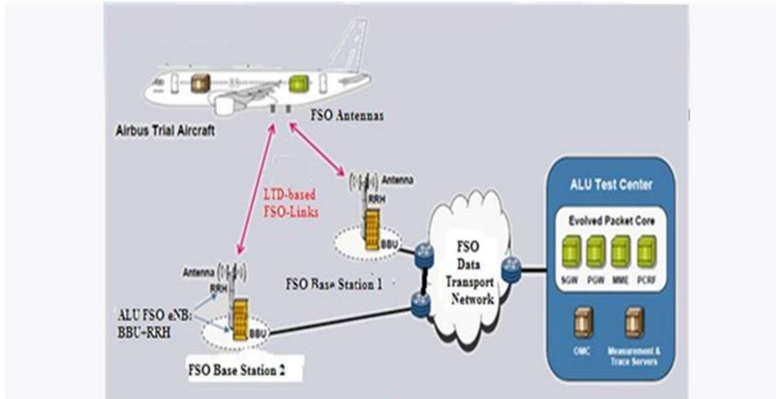

Fig.3 Block diagram of ATG system with laser communication (FSO)

The equipment on the aircraft in such a system should be equipped with several transceivers to be able to maintain communication with several base stations of a ground-based mobile operator (Fig. 4).

Fig.4 Multi-channel laser communication installation

The average annual distribution of cloudiness, for example, on the territory of the USSR according to meteorological observations for 1937 - 1983. [14], shown in Fig. 5.

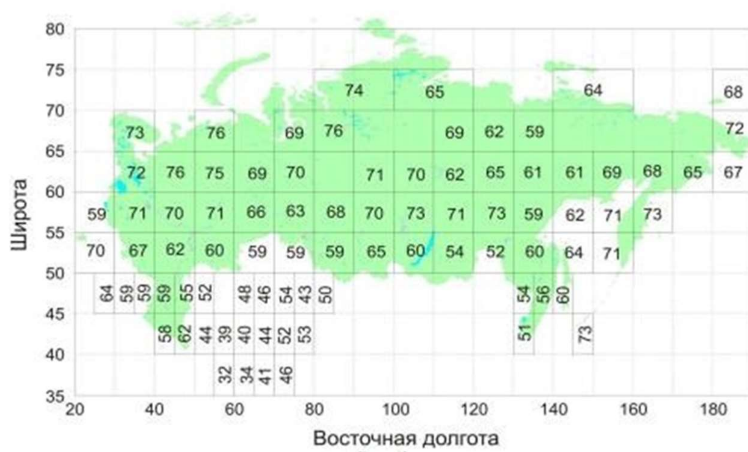

Fig. 5 Average percentage of cloudiness in the territory of the USSR according to meteorological observations for 1937 – 1983

In the figure, the average percentage of cloudiness is given in numbers in cells in a given area during the year. As follows from the above data, in Russia the average percentage of cloudiness is not lower than 60%. The lower part of the figure shows data on the territory of the Central Asian republics of the former USSR, where the percentage of cloudiness decreases to 40% or even lower.

The number of base stations required to organize a transport channel based on laser communication should be selected based on the probability of successful information transmission. Calculations show [14] that for the probability of successful transmission of information to 99%, it is necessary to have at least 5 BTS with an average percentage of cloudiness of 4%.

For the Republic of Uzbekistan, the average annual cloudiness map needs to be updated. Most likely, it will correspond to the zoning adopted by the hydrometeorological center of the Republic of Uzbekistan. It is believed that within the administrative formations, the weather conditions are approximately the same, therefore, to solve the problem, it can be assumed that within each formation the number of sunny days, precipitation, average temperature, the presence of fogs, etc. are the same [16,17.25].

The climatic zoning of the Central Asian region, carried out in 1966, is as follows:

1. Karakalpakstan and Khorezm region.
2. Bukhara and Navoi regions.
3. Samarkand, Jizzakh, Syrdarya and Tashkent regions.
4. Territory of the Ferghana Valley.
5. Kashkadarya and Surkhandarya regions.
6. City of Tashkent.

Using the above zoning, in order to implement the task, in each of them, through a thorough study, select the BTS that satisfy the above conditions. Note that each selected item is an easily scalable structure. When new tasks appear (the number of aircraft simultaneously located in a given area), it is enough to add one receiving device at each point, consisting of an optical system (telescope), a radiation receiver and an interface module, and connect it to an information data transmission channel.

Laser communication, as you know, is a rather complex system, the slightest shift of the emitter can lead to a deviation of the laser beam from the course. Therefore, narrowly directed radiation and the reception of optical waves require careful stabilization of the devices, the orientation of the optical systems of the source to the radiation receiver. Devices that provide the required orientation have been developed and are widely used in space technology [20, 21], which can also be used in the organization of ground-to-aircraft laser communication.

Aircraft avionics may also generate constant, minor vibrations, any of which would be sufficient to send an optical signal inaccurately. To stabilize vibrations, the optical system in space communications is placed on a special anti-vibration platform. It measures the resulting vibrations and produces opposite vibrations to eventually eliminate them [11]. A similar device can also be used to organize laser communication in ATG transport channels.

Conclusion. The Internet on board the aircraft is not yet available in every airliner. This is due to the fact that the installation and installation of systems for receiving and transmitting signals from the Earth is a very expensive process, therefore, the airline charges an additional fee from the passenger for using the Internet. The amount charged from passengers depends on the speed of data transfer, traffic, time of use, and the speed of the Internet connection on board the aircraft is currently low.

The considered version of the organization of the transport channel "land - aircraft" will allow access to the Internet at a speed that is comfortable for passengers. It should be noted that the technology of laser space communication will be further improved many times, and along with this, it will provide new opportunities. Of course, all this will require additional investments by air carriers, but as you know, there is no progress without additional costs.

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