PROTOTYPE OF COMMUNICATION SYSTEM FOR MARS EXPLORATION

Abstract. This manuscript proposes the creation of a communication and navigation system for researchers who need to move away from the base settlement on Mars. One of the main requirements for a communication system is its ease of deployment, so it will be advisable to use satellite facilities. For interplanetary expeditions, the cost of each kilogram of payload is very high, so it is important to ensure that the design of communications satellites is minimized by weight and size criteria. In view of this, one of the possible options for building a satellite communications system on Mars is to use a group consisting of a nanosatellites.

Keywords: communication, navigation, system, nanosatellites, orbit.
There are several projects to colonize Mars. Each of them provides for different scales of settlements, different ways of delivering goods and people, different options for protection against radiation and creating comfortable living conditions. For the colonial settlement on Mars, the first stage involves solving problems related to the construction of all human life support systems in a limited area.

The most probable location of the first colonies is the Mariner Valley [1]. It stretches for more than 4,000 km, has an average width of 200 km and a depth of 11 km (Fig. 1). With an average removal of the Valley from the equator of 850 km, some areas are actually located on it. Recent research in the Mariner Valley has revealed signs of a huge glacier comparable in size to the Sea of Azov. The glacier covers an area at an equatorial distance of 180 to 600 km. If the availability of water ice reserves is confirmed, it will be appropriate to land colonists right here [2].

![Fig. 1. Location of the Mariner Valley and Glacier (ABC)](image)

Usually, the next stages of colonization will be related to the study of the planet's surface, especially the Mariner Valley. It is then necessary to take care of the establishment of a communication and navigation system for researchers who need to move away from the base settlement for long distances.

It is clear that such a system should be based on the use of radio facilities. When determining how to construct a communication system for researchers who are constantly moving on the planet's surface, it is necessary to take into account the fact that the radius of Mars is almost twice smaller than the radius of the Earth, so
the geometric distance of the visible horizon which is not difficult to determine by Pythagorean theorem Eq. (1):

$$d = \sqrt{(R + h)^2 - R^2} = \sqrt{h(2R + h)^2}$$  \hspace{1cm} (1)

where \(R\) – the radius of the spherical planet, \(h\) – the height of the observation point relative to the planet's surface; will be reduced in comparison with terrestrial conditions almost in 1,4 times.

Due to the distance reduction of the visible horizon, and, accordingly, the direct visibility distance, requires a fairly dense location of repeaters (base stations). Building each relay point is a rather complex procedure that requires considerable effort and material resources. With a limited number of researchers, they simply will not be able to physically accomplish this task. Therefore, the usual facilities of radio communication for mobile subscribers, which we are accustomed to using, can not be used to create a communication system on Mars, at least in the early stages of colonization.

Consequently, if one of the main requirements for the communication system is the simplicity of its deployment, it will be advisable to use satellite facilities. In this case, the process of launching satellites into orbit will not require the launch of carrier rockets from the planet's surface. Communication satellites can end up there almost immediately after disconnecting from the cargo ship as it approaches Mars.

For interplanetary expeditions, the cost of each kilogram of payload is very high, so it is important to ensure that the design of communications satellites is minimized by weight and size criteria.

Back in 2013, NASA organized the PhoneSat project, the essence of which was that three nanosatellites (NS) of the CubeSat format, which are built on the basis of conventional smartphones, were sent into space. Additionally, each NS was equipped with a transmitter, lithium-ion battery and solar panel. During the work of the NS, a large number of photographs were sent, and smartphone cameras were used to receive them. This mission proved the possibility of using a large number of NS due to the low cost of such devices - about 7 thousand dollars, while the cost of the classic CubeSat is estimated at 20-40 thousand.
In view of this, one of the possible options for building a satellite communications system on Mars is to use a group consisting of a NS. In any case, the first settlers do not need global communication coverage, so an area that can be formed by clusters of NS in only one equatorial orbit will suffice. In the future, the coverage area can be expanded by creating NS groups in inclined orbits.

Determine the distance from the NS cluster to the boundary of the service area on the Martian surface, which is marked \( a \) in Fig. 2. Note that \( h \) – the height of the orbit of the NS cluster.

Fig. 2. Determining the distance from the NS cluster to the boundary of the service area on Martian surface

The length of the planet’s surface in the equatorial belt Eq. (2):

\[
l_M = 2\pi R
\]

is \( l_M = 21264 \text{ km} \).

The angle \( \alpha \) is found from the Eq. (3):

\[
\alpha = 2\pi / \left( \frac{l_M}{r_K} \right)
\]

where \( r_K \) – the service area radius of the NS cluster.

Then, according to the cosine theorem, the distance \( a \) is determined Eq. (4):

\[
a = \sqrt{R^2 + (R + h)^2 - 2R(R + h) \cos \alpha}
\]

On the Martian surface, the distance between the service areas centers of adjacent clusters \( l_K \) (distance \( AB \)) is determined based on the value of their overlap,
which is denoted in Fig. 3 as $l_Z$ (distance $CD$), according to the Eq. (5):

$$l_K = 2 \sqrt{r_K^2 - l_Z^2} / 4$$

Fig. 3. **Determining between the service areas centers of adjacent clusters $l_K$**

Then the number of clusters in orbit $N$ can be determined by rounding to the nearest larger whole number ratio of the planet’s surface length in the equatorial belt to the distance between the service areas centers of adjacent clusters Eq. (6):

$$N = \text{roundup} \left( \frac{l_M}{l_K} \right)$$

For the example shown in Fig. 4, it is proposed to use only four NS in the cluster. It is obvious that the service area radius of an individual NS $r_{NS}$ will be twice smaller than the service area radius of the NS cluster $r_K$.

Fig. 4. **An example of the service areas location by individual NS**

Then the minimum value of the service areas overlap of the clusters $l_Z$, and in other words the minimum width of the coverage band along the equatorial zone will
be determined Eq. (7):

\[ l_z = 2 \sqrt{r_{NS}^2 + r_{NS}^2} = \sqrt{8} \cdot r_{NS} \]  

(7)

It is necessary to provide means of controlling the NS position in its orbit. Due to the actual absence of a magnetic field on Mars, the methods, that used to NS stabilize and orient, can be of two types: based on flywheel-engines and with jet engine.

Regardless of which stabilization and orientation system will be used, we assume that the control process will be based on the data of small sensors with low current consumption, this requires:

– 6 photosensors (on all faces of the NS) for the NS rough orientation on the Sun and the light, reflected from Mars;

– 3 sensors of angular speeds of rotation around 3 mutually perpendicular axes.

The main advantage of stabilization systems using flywheel-engines is that they do not require fuel on board.

In general, such a system with low power consumption for electric engines (up to 1 W) shows a fairly high efficiency and speed [3–4].

Jet engines create a control moment due to the reaction of the gases passing flow from the nozzle, the axis of which is located at some distance from the center of NS masses. Their location on the edge of the surface in the middle of the face will be most effective.

A common disadvantage of such systems is the limited operating time due to the loss of working fluid. The very principle of mass ejection leads to the need to create a reserve, which increases the NS weight at startup.

As such devices it is possible to use ion engines, the main advantage of which is considered to be efficiency. Because ions have a speed an order of magnitude higher than the rate of gases flow from the rocket engine, to change the NS speed by a given value, they need an order of magnitude less fuel.

According to a press release from the Massachusetts Institute of Technology, a group of American engineers have developed special ultra-compact ion engines to correct the orbit of the NS [5].

The dimensions of the ion accelerator are 10x10x2 mm. The fuel supply, or in
other words the reactive mass, will be stored directly inside the engine in liquid form and will come out through a microscopic hole where its particles are ionized and accelerated by an electric field.

The MicroThrust group of micromotor developers has announced the creation of the first working prototype of a new generation ultra-compact space engine using matrix micro nozzle technology [6-7].

The working prototype created by Europeans differs in high economy and traction efficiency.

One ion accelerator motor module with a centimeter matrix of 1000 micro nozzles consumes a total of 4 watts.

At 500 micro nozzles, the power of such an engine is estimated at only 50 micronewtons, but in conditions of vacuum and near-zero gravity, it is sufficient to adjust the NS orbit.7

Since the orientation systems on flywheel-engines do not allow changing the NS orbit, it is best to use a combined system, which is additionally equipped with ionic engines, which will be used mainly to change the NS orbit, which will significantly increase their service life, as well as to carry out the planned departure from orbit after the end of exploitation.

In the general case, the cluster will include the NS to communicate with subscriber terminals, the NS to concentrate and switching the load inside the cluster, to communicate with neighboring clusters, and to communicate with a station on the Mars surface. Since the distance between the NS cluster is only a few tens of meters, the interaction between them can be carried out using Wi-Fi or laser beam. The composition of the cluster is explained in Fig. 5.

For the example shown in Fig. 4, four devices are required to communicate with subscriber terminals. The function of concentration and switching of the load inside the cluster, communication with neighboring clusters, as well as communication with the station on the Mars surface will be performed by another NS, which must be duplicated. Thus, the cluster must be at least 6 NS.

It is proposed to use a conical spiral antenna to form the NS radiation pattern for communication with subscriber terminals [8].
The radiation pattern width of an individual NS by the cosine theorem in the notation of Fig. 2, is determined Eq. (8):

$$\theta = \arccos \left( \frac{a^2 + (R + h)^2 - R^2}{2a(R + h)} \right)$$

If the service area radius of an individual NS is 650 km, and the height orbit of the NS is 700 km, the width of the radiation pattern will be $\theta = 53$ degrees.

For the average frequency of interaction between the NS and the subscriber terminal 1.6 GHz at the antenna length $l = 18$ cm and the spiral diameter $d = 6$ cm, the gain is $G = 9 - 11$ dB. Such an antenna is a spring when coiled that will occupy a volume of about $V = 0.9$ cm$^3$, that is $0.9\%$ of the CubeSat-1 total volume [9].

Let’s evaluate the possibility of ensuring the NS autonomous operation based on of energy performance.

According to Reference 10, the attenuation for an ideal isotropic antenna in free space is determined Eq. (9):

$$L = 32.4 + 20 \lg(f) + 20\lg(d),$$

where $f$ – frequency in MHz, $d$ – distance in km.

Therefore, in the center of the cluster service area (distance up to 1000 km) attenuation is $L = 156$ dB.

The modern receivers sensitivity of personal satellite communication terminals is about 118 dB. Given the antenna gain to $G = 11$ dB, the losses associated with the
formation of a spiral antenna signal with a circular polarization about 3 dB, as well as possible losses in the atmosphere to 3 dB, radiation power with a "margin" of 3 dB should be:

\[ P = 156 - 118 - 11 + 3 + 3 + 3 = 36 \text{ dB}, \]

that is 4 watts. The transmitter efficiency, as a rule, does not exceed 30%, which corresponds to a power consumption of 14 watts. Additionally, the receiver requires 5 watts.

It is necessary to take into account the fact that part of the electric power is spent on recharging the battery, which ensures the operation of the NS while it is in the shadow of the Mars. In addition, the stabilization system consumes about 4-8 watts (briefly).

Based on this, the solar battery should provide a power supply of 45 watts [9].

The average value of the solar constant for the Earth is 1367 W/m², because the distance from the Sun to Mars is greater - 1,524 astronomical units, then the solar constant for Mars will be about 590 W/m². Today, the vast majority of solar panel manufacturers offer products with an efficiency not exceeding 20-35% [9]. Provided the surface location of the NS solar battery perpendicular to the direction of sunlight propagation (with a tolerance of a slight deviation up to 15 degrees), the produced electric power can be found Eq. (10):

\[ P = 590 \times \eta \times S \]

where \( \eta \) – efficiency of the solar battery; \( S \) – surface area of the solar battery.

To obtain the required power supply, the surface area of the solar battery must be not less than Eq. (11):

\[ S = \frac{P}{590 \times \eta} \]

that is \( S = 0,38 \text{ m}^2 \). The NS standard size of the CubeSat-1 format is a cube with a side of 10 cm. If two symmetrical batteries are used, one side of which is equal to the specified 10 cm, the other, if the calculated value is rounded up, a multiple of 10 cm - should be about 2 m long.

Based on this and taking into account the need for a battery in the NS design,
its format can be defined as CubeSat-3. The total weight of such a structure will be within 9 kg.

The results of the parameters calculation of the nanosatellite grouping for the case shown in Fig. 4 are presented in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of the NS orbit, $h$, km</td>
<td>700</td>
</tr>
<tr>
<td>Service area radius of a separate NS, $r_{NS}$, km</td>
<td>650</td>
</tr>
<tr>
<td>Service area radius of a NS cluster, $r_{K}$, km</td>
<td>1350</td>
</tr>
<tr>
<td>Overlap magnitude of service areas of adjacent clusters, $l_Z$, km</td>
<td>1838</td>
</tr>
<tr>
<td>Number of clusters in orbit, $N$</td>
<td>12</td>
</tr>
<tr>
<td>Number of NS in the cluster</td>
<td>6</td>
</tr>
<tr>
<td>Total number of NS in the system</td>
<td>72</td>
</tr>
<tr>
<td>Minimum cost of NS grouping, thousands of dollars</td>
<td>504</td>
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</tbody>
</table>

It should be noted that in the early stages of colonization in the Mariner Valley, it is sufficient to provide coverage only in the area located in the northern hemisphere from the equator of Mars. Then the number of NS clusters will be reduced to 3, and the total number of NS grouping - 2 times that specified in the table.

References:

