Comparison of geostationary and low-orbit “round dance” satellite communication systems

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Abstract. Modern satellite navigations systems utilize high-orbit (mostly geostationary) and low-orbit satellites. Both satellite types have their advantages and disadvantages. A global communication system requires at least three or five GEO satellites with a life of 10 years, with each satellite costing around $200 million. Low-orbit global communication systems of the “round dance” type must have from hundreds to thousands of satellites. Their orbit life can range from 2 to 5 years; their cost must be between $1 million and $20 million. At this stage, there is a wide range of means for launching communication satellites into orbit, a large range of metal and composite structural materials. In addition, there are methods of designing, manufacturing, and testing communication satellites, as well as software and hardware for satellite control have been developed. So, the problem of economic optimization of communication satellite constellations becomes relevant. The paper presents the results of the comparative engineering and economic analysis of two types of satellite constellations.

1. Introduction
The idea of creating global satellite navigation systems was first proposed by a British philosopher and science fiction writer Arthur Clarke in 1945. However, this idea could only be implemented with the advent of launch vehicles. Given the evolution of the society from the industrial stage to the information stage, satellite communication is one of the most thriving areas of the current society's infrastructure [1-6]. Satellite communication is powered by stationary or mobile ground stations. Russian satellite communication systems are pioneered by such scientists as M.F. Reschetnev, M.R. Kaplankov, N.I. Kalashnikov and L.Ya. Kantor.

In Russia, USA, Europe, Japan, and China, there are intense efforts underway to create geostationary communication satellites with non-deployable high-gain antennas and large transformable reflectors [7-18]. Usually, these antennas are made out of composite material with a unique combination of mechanical and thermal-physical characteristics. Separately from GEO communication satellites, researchers develop LEO communication systems forming clusters of the “round dance” type. Their satellites are directly visible, and they relay the received signal from one satellite to another. “Round dance” type satellites are equipped with relatively simple compact transceiver antennas.

Currently, satellite communication comprises around 5% of total communication. However, there is a growing demand for satellite communication lines. Compared to ground long-distance communication lines [6], satellite communication is more viable at a distance greater than 800 km. The main problem
of this area of applied space research is to optimize the price to quality ratio of the space-based communication system.

The goal of this paper is to investigate a multi-dimensional surface boundary of the space of engineering and cost parameters separating economically viable GEO and LEO satellite communication systems. The investigation can reveal the engineering and cost parameters such that low-orbit "round dance" satellite constellations are capable of competing with GEO satellite communication systems.

The paper's novelty lies in the fact that there is still little research in the area of low-orbit satellite communication systems.

2. Specifics of the satellite communication systems

The advantage of satellite communication is related to the following factors:

- The ability of multi-fold increase of traffic transmitted over great distance to the areas with different climate and terrain.
- Round-the-clock and all-weather accessibility to a large number of users at a moderate cost.
- Variability of frequency ranges selectively tuned to exchange data with stationary and mobile transmission/reception stations on the ground, underwater, in air and space.
- Retransmission equipment for amplifying the input signal power and switching to other frequency ranges during transmission is an integral part of communication satellites.

Current satellite communication systems are placed on three types of orbits with different shapes and parameters: practically circular low-Earth orbits (LEO) or elliptic high-apogee and high circular geosynchronous orbits (HEO), with the primary orbit being the geostationary orbit (GEO) [1-6].

GEO has the following advantages:

- No need to redirect ground antennas during round-the-clock continuous operation.
- Input signal power stability due to the constant distance between a satellite and a ground station and no Doppler frequency shift.
- High Earth surface coverage that paves the way towards creating a global communication system using three satellites.

The disadvantages of GEO are as follows:

- Signal delay up to 0.6 s due to propagation of electromagnetic waves over a great distance between a satellite and a ground station.
- Unfeasibility of radio communication in the high latitude areas and on the poles of the Earth.

In Russia, the latter disadvantage is compensated by launching satellites on elliptic orbits with the apogee in the Northern hemisphere (~ 40 thousand km) and the perigee in the Southern hemisphere (~ 400-600 km). These orbits had started being utilized with the launch of the “Molniya” communication satellite in 1965.

The common drawback of high-orbit systems is the need for sophisticated, bulky, costly, and energy-consuming ground station equipment. This drawback has recently spurred the development of LEO satellite repeaters of generic data and voice data.

The advantages of LEO-based communication systems are as follows:

- Lower cost of deploying greater payloads to low orbits compared to high orbits.
- Simultaneous deployment of constellations comprised of several small satellites that improve the reliability of communication systems.
- Reduced onboard power requirements due to relatively small distances between satellites and ground stations.
- Simpler equipment of ground stations.
- Feasibility of radio communication in the high latitude areas and on the poles of the Earth.

Generally, LEO-based communication systems must have from several tens to several hundreds of satellites providing a high level of system redundancy for the required coverage zones. As estimated in [3], a communication system of 60…70 satellites equally spaced in ascending nodes of the orbit can cover the whole surface of the Earth. The time of satellite flight over a subscriber can range from 10
minutes to 20 minutes. The orbit altitude of around 900 km, the inclination of 74º, and the zone of subscriber radio visibility above the 7º local horizon correspond to the satellite service zone radius of more than 2500 km.

LEO-based communication systems have the following disadvantages:

- Small communication period with one satellite and small instantaneous service zone;
- Smaller active life compared to other systems due to degradation of characteristics caused by the influence of the radiation belts and atomic oxygen;
- Orbit evolution during deceleration in a highly rarified atmosphere.

The comparison of two satellite communication systems on GEO and LEO is shown in Table 1 [5].

### Table 1. Comparison of communication systems on GEO and LEO

| Type of orbit | GEO | LEO |
|---------------|-----|-----|
| Orbit altitude, km | 35750 | 200 – 1200 |
| Number of satellites in a constellation for continuous global coverage, pcs. | 3 | 48 – 72 |
| Coverage zone of the Earth surface by one satellite (elevation – 5º), % | 34 | 3 – 7 |
| Satellite radio visibility zone dwell time, h | Continuous | 0.15 – 0.25 |
| Signal delay, ms: | | |
| - regional communication | Over 500 | 20 – 70 |
| - global communication | – | 170 – 300 |
| Switchover time, min: | | |
| - from one satellite to another; | Not required | 8 – 10 |
| - from one beam to another | 10-15 | 1.5 – 2.0 |
| Maximum relative Doppler shift | ±10⁻⁸ | ±(1.8…2.4)⋅10⁻⁵ |
| Elevation at the service zone boundary, º | 5 | 10 – 15 |

### 3. Comparison of satellite communication system

The results of comparing two types of satellite constellations are shown below:

a) The system with big satellites with transformable umbrella type reflectors with a diameter under 100 m operating on GEO. Satellite cost is $200 million, deployment cost using the “Proton” launch vehicle is $80 million. The system requires 3-5 satellites having a life of 10 years.

b) The system with small “round dance” satellites tightly placed within direct visibility on LEO (600-800 km). The satellite cost is $1–20 million. The satellites are launched in a cluster of 100 satellites at a time. The launch cost using the "Falcon-9" launch vehicle is $50 million. The system will require 1000 satellites with the life from 2 to 5 years.

#### 3.1. Satellite constellation cost vs. the number of big satellites

Table 2 shows the change of satellite constellation cost with the change of the number of big satellites from 3 to 5 with the fixed cost of satellite and the satellite deployment cost.
Table 2: Satellite constellation cost vs. the number of big satellites

| Parameter Name               | Unit       | Number of satellites, pcs. |
|------------------------------|------------|----------------------------|
|                              |            | 3  | 4  | 5  |
| Satellite life               | Years      | 10 | 10 | 10 |
| Total number of satellites   | pcs.       | 3  | 4  | 5  |
| Satellite cost               | $ million  | 200,00 | 200,00 | 200,00 |
| Cost of all satellites       | $ million  | 600 | 800 | 1000 |
| Launch cost of one launch vehicle | $ million | 80 | 80 | 80 |
| Number of satellites per launch | pcs     | 1  | 1  | 1  |
| Number of launch vehicles    | pcs.       | 3  | 4  | 5  |
| Deployment cost              | $ million  | 240 | 320 | 400 |
| Constellation cost           | $ million  | 840 | 1120 | 1400 |

With all else being equal, the constellation cost increases by $280 million or by 33% (figure 1) with each additional satellite.

![Figure 1](image.png)

Figure 1. Satellite constellation cost vs. the number of big satellites

3.2. Satellite constellation cost vs. the number of small satellites

Table 3 shows the results of satellite constellation cost calculation for small satellite unit costs of $1 million and $20 million; the satellites are launched in a cluster using the "Falcon-9" launch vehicle.
Table 3. Constellation cost vs. the cost of small satellite

| Parameter name          | Unit           | Minimum satellite cost | Maximum satellite cost |
|-------------------------|----------------|------------------------|------------------------|
| Satellite life          | Years         | 5                      | 5                      |
| Total number of satellites | pcs.    | 1000                   | 1000                   |
| Satellite cost          | $ million     | 1                      | 20                     |
| Cost of all satellites  | $ million     | 1000                   | 20000                  |
| Launch cost per one launch vehicle | $ million | 50                     | 50                     |
| Number of satellites per launch | pcs.    | 100                    | 100                    |
| Required number of launch vehicles | pcs.   | 10                     | 10                     |
| Cost of orbital deployment | $ million | 500                    | 500                    |
| Constellation cost      | $ million     | 1500                   | 20500                  |

3.3. Satellite constellation cost vs. the life of small satellites

Table 4 shows the results of calculating constellation cost for the satellite life of 2 and 5 years with continuous operation of the system for five years. For the calculation, it is assumed that the average satellite cost is $10 million, and the "Falcon 9" launch vehicle deploys 100 satellites simultaneously. The decrease of satellite life by 2.5 times will require a proportional increase in the number of launches.

Table 4. Satellite constellation cost vs. small satellite life.

| Parameter name          | Unit           | 5 Satellite life, years | 2 Satellite life, years |
|-------------------------|----------------|-------------------------|-------------------------|
| Total number of satellites | pcs.    | 1000                    | 2500                    |
| Satellite cost          | $ million     | 10                      | 10                      |
| Cost of all satellites  | $ million     | 10000                   | 25000                   |
| Launch cost per one launch vehicle | $ million | 50                     | 50                     |
| Number of satellites per launch | pcs.    | 100                    | 100                    |
| Required number of launch vehicles | pcs.   | 10                     | 25                     |
| Cost of orbital deployment | $ million | 500                    | 1250                    |
| Constellation cost      | $ million     | 10500                   | 26250                   |

The calculations show that constellations comprised of satellites with greater life have economic advantages over constellations comprised of satellites with small life. If satellite life decreases from 5 years to 2 years, the small satellite constellation cost increases by a factor of 2.5 up to $26250 million.

4. Comparison of cost of satellite constellations

Tables 5 and 6 show the results of comparing the cost of constellations of big and small satellites with different life ensuring continuous operation of the communication system for ten years. In the calculations, it is assumed that 20 cluster launches of the “Falcon-9” launch vehicle will be required over ten years with the small satellite life of 5 years. The average cost of a small satellite is set to $10 million and $1 million.
same cost would be able to deploy more than 100 communication satellites on LEO. Another way of reducing the cost of the “round dance” constellation is to reduce mass and overall dimensions of each satellite so that the "Falcon-9" launch vehicle or another launch vehicle with the same cost would be able to deploy more than 100 communication satellites on LEO.
5. Conclusions

1. Comparison of two types of satellite constellations revealed that the total cost of deploying a constellation of big satellites on GEO is far less than the cost of a constellation of small satellites on LEO due to higher life of big satellites, and, consequently, the smaller cost of orbital deployment over the ten years even, taking into account the 200x cost gap between small and big satellites.

2. However, one must not exclude the possibility of significantly reducing the cost of small satellites below $0.2 million, reducing their dimension and mass, and creating new launch vehicles with higher payload capacity, which will improve the economic viability of the “round dance” LEO satellite constellations.

3. Engineering and economic issues of disposing of decommissioned small communication satellites have to be further researched. The problem of removing space debris from LEO is already urgent, and it will be further aggravated by hundreds and thousands of new small satellites.

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