Prospective directions for the development of microwave frequency standards for satellite navigation systems

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Abstract. The state of essential various quantum standards of GNSS frequencies for today are collected and presented, the results of analysis in the direction of modernization of time synchronization systems in global navigation satellite systems are presented. The most perspective directions of modernization of global navigation satellite systems are mentioned – the development of new atomic clocks on the mercury ions -199. The data on experimental satellite gives encouraging results.

1. Introduction

Currently, global navigation satellite systems (GNSS) are constantly being developed and modernized [1-9]. The modernization process is determined by the structure of GNSS construction and by the tasks solved by it [8-14]. Four satellite constellations are currently deployed in outer space: the American system - GPS, the Russian system - Glonass, the European system - Galileo and the Chinese system - BDS [13-16].

The most important function of GNSS is to determine the location of an object and provide users with three-dimensional information about its coordinates. For positioning an object using the GNSS system, the time and coordinate system are of critical importance [5-8, 10, 17-22]. Any deviation in the value of time between satellites can have a huge impact on the accuracy of positioning [16, 23].

The coordinate system in GNSS is a reference system. It consists of the origin O, the X-axis, the Y-axis and the Z-axis, in the usual case, the origin O is in the center of mass of the Earth, the X-axis and the Z-axis are directed in different directions, the Y-axis makes a rectangular coordinate system with the X-axis and the Z-axis. For proper operation of the positioning system, while there is no single system, they can replace each other with complex mathematical calculations, this is not very convenient for everyone. This often creates problems. Therefore, it is important to determine the promising directions for the development of GNSS in order to reduce these problems to a minimum in the future.

In addition, the orbits of many satellite navigation systems are filled with space debris (decommissioned satellites). There are more and more of them every year. These satellites create problems both in the operation of guidance systems and in the placement of new satellites in orbits [29, 30, 38-40]. This must also be taken into account when determining the promising directions for the development of satellite navigation systems. The increase in the service life of the satellite, which is
now determined by the life of the quantum frequency standard, is a reduction in the rate at which the orbits are filled with "space" debris. This will gain time before an effective system for clearing orbits from "space" debris appears in space. The number of failures in the GNSS work every year due to the "space" garbage increases.

2. Analysis of characteristics of satellite space constellations for navigation systems

All navigation satellites GPS, Glonass, Galileo operate in Medium Earth Orbits (MEO), but each system has a different number of satellites in orbit and a different period of satellite rotation, BDS-3 uses a constellation of 3 orbits: Inclined Geosynchronous Orbits (IGSO), Geostationary Earth Orbits (GEO), and Medium Earth Orbits (MEO), the number of satellites and the rotation period of satellites in each orbit is also different [15, 16, 24-28]. In table 1 shows the data on the different systems.

| System | Orbit altitude (km) | Satellite orbit | Orbit inclination | Satellite rotation period |
|--------|---------------------|----------------|-------------------|--------------------------|
| GPS    | 20200               | MEO            | 55°              | 11 h. 58 m.             |
| Glonass| 19100               | MEO            | 64.8°            | 11 h. 51 m.             |
| Galileo| 23222               | MEO            | 56°              | 14 h. 4 m. 45 s.        |
| BSD-3  | 21528/35768/35768   | MEO/GEO/IGSO   | 55°/0°/55°       | 12 h. 53 m./24 h./24 h. |

Table 1. Data on the different system.

Each navigation system uses a different time system: GPS - GPST, Glonass - Glonass-ST, Galileo - GST, BDS - BDT. These time systems are linked together by Coordinated Universal Time (UTC). The UTC time system is based on international atomic time (TAI). There is no extra second in GPST, GST, and BDT after time starts, and there is an extra second in Glonass-ST. Each navigation system has its own coordinate system: GPS coordinate system (WGS-84), Glonass coordinate system (PZ-90), Galileo coordinate system (GTRF), BDS coordinate system (BDCS).

To transmit navigation signals, GPS, Galileo and BDS use code division multiple access (CDMA) technology, while traditional Glonass uses frequency division multiple access (FDMA), currently Glonass supports CDMA. Each system operates in different bands and has different carrier frequencies, in table 2 shows the carrier frequency data of different systems.

From the analysis of the data in table 2, it follows that GPS (L1), Galileo (E1), BDS-3 (B1) have the same carrier frequency 1575.42MHz, GPS (L5) and Galileo (E5a) have the same carrier frequency 1176.45MHz. This shows that the systems can easily be integrated with each other in case of a merger. This is one of the possible directions of modernization of the entire GNSS.

| System | Range            | Carrier frequency (MHz) |
|--------|------------------|-------------------------|
| GPS    | L1, L2, L5       | 1572.42/1227.60/1176.45 |
| Glonass| G1, G2, G3       | 1600.995/1248.06/1202.025 |
| Galileo| E1, E5a, E5b, E6 | 1575.42/1176.45/1207.14/1278.65 |
| BSD-3  | B1, B2, B3       | 1575.42/1191.259/1268.52 |

Table 2. Formatting sections, subsections and subsubsections.

The time system in GNSS is linked to the atomic clock of the satellite, which can also be called the heart of the whole satellite system. The GPS satellites use atomic clocks with rubidium (Rb-87) and passive hydrogen maser (PHM), the Glonass satellites use atomic clocks with cesium (Cs-133). The Galileo and BDS satellites (BDS-3) use two types of atomic clocks: passive hydrogen maser (PHM) and rubidium atomic frequency standard (RAFS). There is an experimental satellite with a mercury ion atomic clock (Hg-199) in space. In Figure 1 shows a diagram of the change in the number of
atomic clocks in orbit over 40 years. The total number of atomic clocks on active satellites is shown in parentheses.

**Figure 1.** The estimated number of GNSS-grade or better SAFSs sent in space as of 2 March 2021.

Operational data have shown that the atomic clock PHM (Galileo) has the greatest long-term stability of the output characteristics (it does not require constant adjustment of the scale during a communication session with the Earth) [23, 29-33].

3. Analysis of metrological characteristics of quantum standard frequencies

Frequency stability is an important metrological characteristic for quantum standard frequencies, usually described using Allan deviation. Figure 2 and Figure 3 shows 2020 data on Allan deviation for various models of atomic clocks placed on satellites, including new designs of passive hydrogen masers and atomic clocks on mercury ions -199.

**Figure 2.** The Allan deviations of different current space atomic clocks. Graphs 1, 2, 3, 4, 5, 6, 7 and 8 correspond to the following atomic clock: Cs-133 – GPS; RAFS spec. – Galileo; RAFS – BDS; RAFS – Galileo; PHM–BDS; Cs-133 – Glonass; PHM – Galileo; Radioastron H-maser – GPS and Galileo.
Figure 3. The Allan deviations of different current space atomic clocks and station communication on Earth. Graphs 1, 2, 3, 4, 5, and 6 correspond to the following atomic clock: Cs-133 – Glonass; PHM and RAFS – GPS; JPL 199Hg ion – GPS experimental – USA; Leonardo RAFS – Galileo; PHM – ship communication station; PHM – communication station on Earth.

Analysis of Allan deviation data for different models of atomic clocks (Figure 2), shows that PHM have the best values than other models of atomic clocks. Their disadvantages are limited operating life, high requirements for temperature stabilization and large size compared to atomic clocks on rubidium atoms.

The most prospective direction in the modernization of GNSS is the development of atomic clocks on mercury ions -199 [34-37]. These standards do not have the disadvantages of PHM noted above. The only problem is to work out the design of the Pauli trap while reducing its size and weight for the satellite system. Data on the experimental satellite give encouraging results.

4. Conclusion
The analysis of all the data obtained shows that the two directions of GNSS modernization are the most promising. Creation of a single GNSS system on Glonass orbit using two satellite orbits of the Chinese BDS system. This will solve many of the problems discussed in this article. Especially with the removal of space debris from orbit. The Glonass orbit is the lowest. Forced removal (currently implemented technology on the space robot Ullius) from this orbit of spent satellites will not create problems for other satellite navigation systems.

Or the replacement of all the satellites by new ones with atomic clocks on mercury ions -199. This will reduce the number of satellites in orbit, since the atomic clocks on mercury ions -199 needs almost no adjustment from Earth. The resource of the optical system of this clock is very long (longer than the electronics of the satellite). It is necessary to note that orbits are very cluttered with satellites, taken out of operation and there is less and less place on them. It will also reduce the rate at which space debris fill up orbits.

From this point of view, and taking into account the control of satellite constellation compared to global satellite navigation systems the Chinese system - BDS is the most reliable.

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