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# Improving the navigation spacecraft radio visibility with signal processing algorithms usage

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**Abstract.** The article deals with topical issues of spacecraft external design for the global navigation satellite system (GLONASS). The development and analysis of data processing algorithms are considered a part of the external design phase. Data for processing algorithms was obtained from real orbital grouping spacecraft. Mathematical modelling was performed based on real data to analyse navigation signals propagation conditions from GLONASS satellites. Implementation of mathematical modelling approach included such aspects as finding the optimal antenna pattern and filtering radio frequency signals. Theoretically optimal antenna directivity patterns were implemented taking into account available data about satellite orbital parameters. Bessel, Butterworth, Chebyshev and elliptic filters were used as standard filtering methods. Modified low-pass filtering algorithm was considered as an improved filtering algorithm. Application of the modified filtering method allowed to reduce geometric dilution of precision value in the consumer positioning case. Obtained results are applicable to design possible options for improving the existing GLONASS orbital group.

## 1. Introduction

Space technology development is a process that requires an enormous amount of resources: high technology intensity, significant labor costs, long development periods and spacecraft (SC) testing. Moreover, it is necessary to support continuous operation of expensive special space complexes and onboard equipment.

This article covers data processing algorithms development for the global navigation satellite system (GLONASS) orbital SCs. Subsequent data processing analysis helps to increase positioning accuracy for objects of interest. This is achieved by representing GLONASS orbital group on the level of external design of space satellite system [1]. On that level a model is selected for designing a location determination system, calculating theoretically optimal antenna system directivity patterns, implementing filtering algorithms of radio frequency signals.

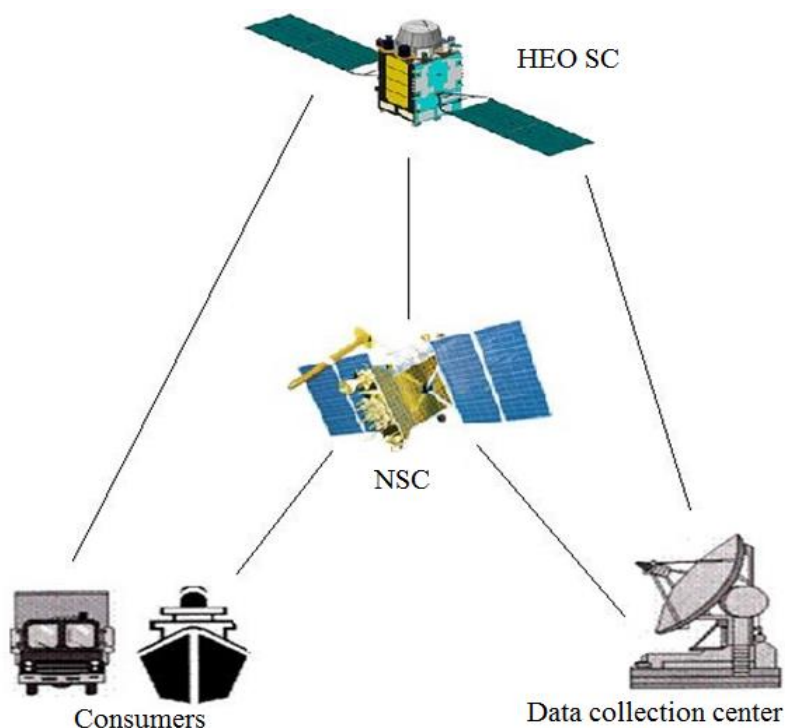
## 2. Model selection for designing the location determination system

As a basic model of consumer location determination in GLONASS orbital grouping a 4-level system is considered.

The first level – consumer's device receiving navigation signals to directed antenna from several navigation spacecraft (NSC) in the visibility zone simultaneously. The second level of location determination system includes NSCs operating in an average circular orbit. A separate communication channel is used for transferring consumer navigation parameters to a data collection center (third level).



The session of navigation parameters measurement and transfer from NSC starts upon request from a data collection center. To get information regarding NSC movement nature high elliptical orbit (HEO) SCs are used (fourth level), which are communicated through radio visibility sessions. Fourth level SCs can also communicate with consumer devices. The presented scheme of 4-level consumer's location determination system is presented in figure 1.



**Figure 1.** Scheme of 4-level consumer's location determination system.

A case of HEO SC placement is considered with evolving orbital parameters. A data fragment on SC movement parameters in HEO-1 (high elliptical) orbit is given in Table 1.

**Table 1.** Data fragment on spacecraft movement parameters in HEO-1 orbit.

Date (Year. Month. Day)	Number of coils	Time in format (hours: minutes: seconds)	Perigee height $H_{\text{perig}}$ (km)	Eccentricity, $e$	Declination, $i$ ( $^{\circ}$ )	Perigee argument $\omega$ ( $^{\circ}$ )	Apogee height $H_{\text{apog}}$ (km)	Absolute longitude of ascending node $\Psi$ ( $^{\circ}$ )
15.03.21	1	6:59:54	32750	0.07215	64.8	270	38834.2	0
20.02.18	1801	7:55:09	32837.6	0.0701	63.96	260.9	38749	0
25.03.21	3664	4:39:24	33020.6	0.06575	61.81	254.4	38565.3	0
...	...	...	...	...	...	...	...	...
15.03.21	1	6:16:14	32750.0	0.07215	64.80	270.0	38834.2	350
20.02.18	1801	7:11:31	32954.0	0.06734	63.53	260.4	38632.3	350
25.03.21	3664	3:55:24	33213.7	0.06117	60.99	252.7	38371.7	350

First the change ranges are defined of orbital movement heights regarding GLONASS satellite grouping. This action allows to calculate satellite operation ranges in the orbit of certain type. Operation

ranges include height ranges no less than 11900 – 1200 km (threshold plane height) [2]. Design of a model that reflects satellite movement trajectory in HEO-1 type orbit and height threshold value is done with the aim of defining conditions of possible radio communication sessions between SC in HEO and NSCs operating in average circular orbits. To achieve this, it is necessary to consider the change of perigee height value  $H_{\text{perig}}$  for the 10-year period of SC operation at various values of ascending node longitude  $\Psi$ .

Perigee height changes in the range of values from 28494.58 to 33445.73 km. Satellite movement trajectory in HEO-1 type orbit is located higher than the GLONASS satellite grouping movement trajectory (relative height threshold  $H_{\text{lim}} = 19000$  km), which allows to make a conclusion that mounting upper antennas on SC is unnecessary.

### 3. Calculation of theoretically optimal antenna system's directivity patterns

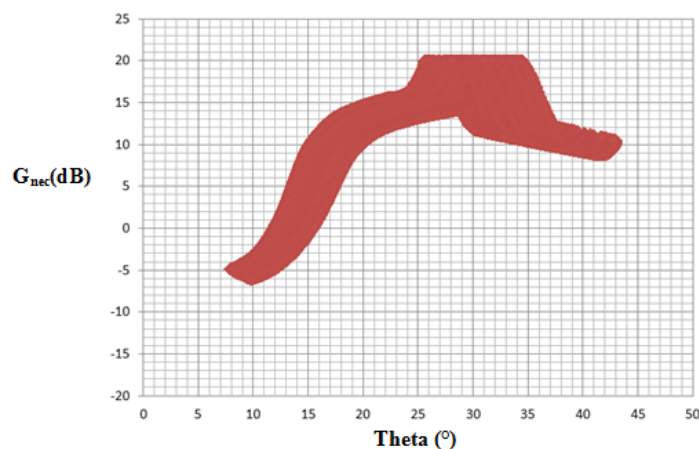
For modelling purposes a case is considered of SC movement in HEO-1 orbit with the following parameter values:  $H_{\text{perig}} = 31034.00$  km,  $H_{\text{apog}} = 40548.50$  km,  $i = 67.76^\circ$ . For the given parameter values of HEO SC movement satellite receiving antenna parameter calculation is done with the aim of obtaining antenna directivity patterns close to optimal.

Taking into account the features of antenna system design for GLONASS NSC [3] the receiving antenna parameters of a satellite moving in HEO-1 type orbit are provided in Table 2.

**Table 2.** Receiving antenna parameters of a satellite moving in HEO-1 type orbit.

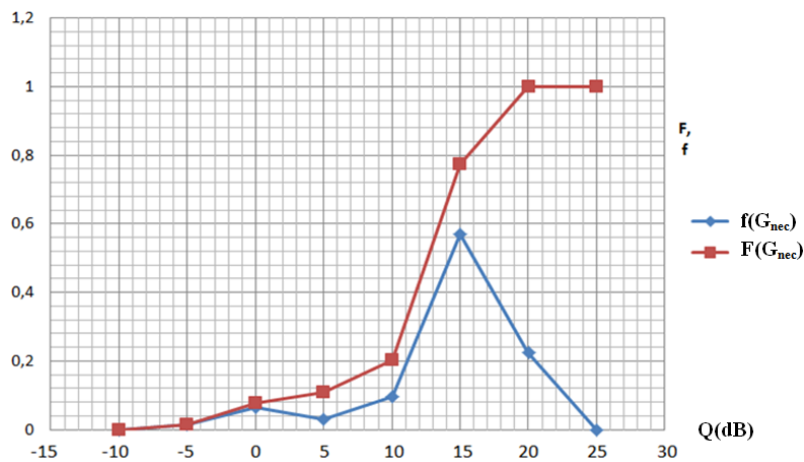
Theta ( $^\circ$ )	GXmtr (dB)	G <sub>nec</sub> (dB)
8.978	13.6055	-5.4123
8.919	13.6379	-5.4450
8.861	13.6688	-5.4762
...	...	...
42.003	-7.6703	11.8779
42.043	-7.7377	11.7281
42.082	-7.8053	11.5732

Table 2 includes 3 columns: Theta ( $^\circ$ ) – half-open degree, GXmtr (dB) – gain factor, G<sub>nec</sub> (dB) – lacking radio signal gain. G<sub>nec</sub> parameter is calculated by the following formula:  $G_{\text{nec}} = Q_{\text{thresh}} - C/\text{No}$ , where  $Q_{\text{thresh}} = 35$  (dB \* Hz). Dependencies of G<sub>nec</sub> from Theta degrees are shown in figure 2.



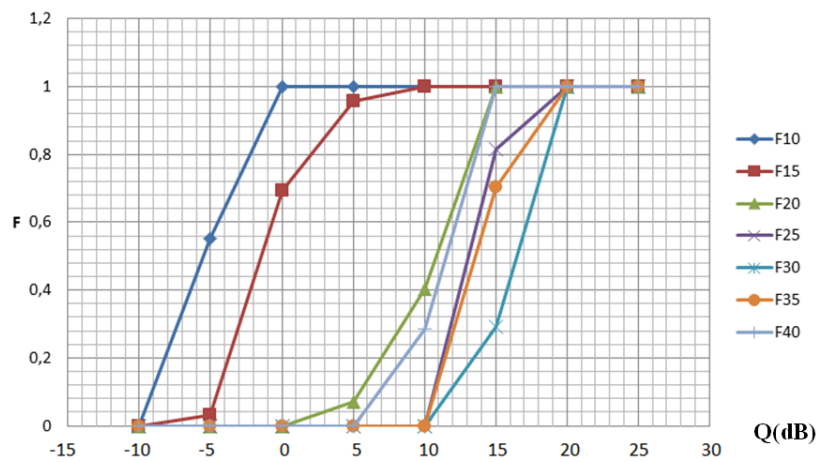
**Figure 2.** Dependencies of G<sub>nec</sub> from Theta.

Calculated values of probability density  $f(G_{\text{nec}})$  and probability function  $F(G_{\text{nec}})$  are provided in figure 3.



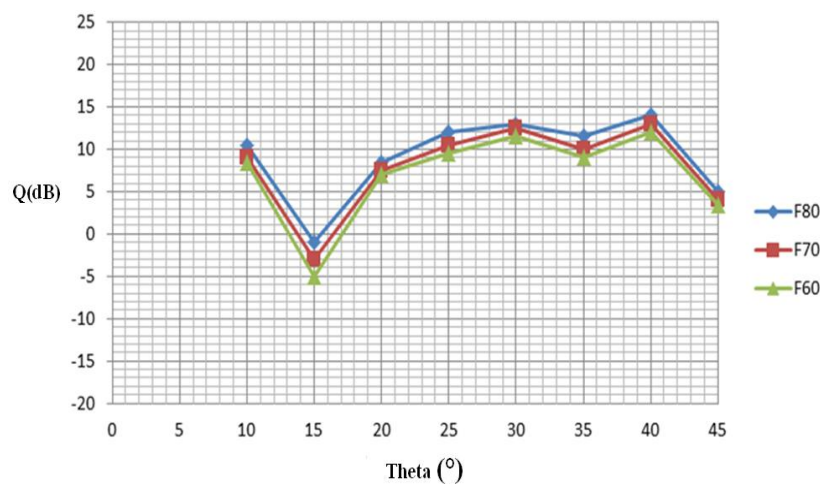
**Figure 3.** Probability density  $f(G_{nec})$  and probability function  $F(G_{nec})$ .

Probability function  $F(G_{nec})$ , taking into account the lacking radio line gain  $G_{nec}$ , for different Theta angle intervals, where  $\Theta \in [5; 45]$ , is shown in figure 4.



**Figure 4.** Probability function  $F(G_{nec})$  for different Theta angle intervals.

The necessary directivity pattern depending on the percentage of geometrically accessible measurements (60%, 70%, 80%), restricted by antenna system's sensitivity, is shown in figure 5.



**Figure 5.** Necessary directivity pattern.

The obtained close to optimal antenna directivity pattern is used for further calculation of support conditions of radio visibility sessions between SC in HEO and NSC.

#### 4. Radio frequency signals filtering algorithms

To solve consumer's navigation determination problem (location and kinematic parameter vector determination) the signals received by antennas with calculated directivity patterns should have such a structure so that it was possible to separate them and relatively accurately measure radio signal parameters (delay, Doppler frequency offset, phase) [2]. Because of that, in order to effectively receive radio signals, the following requirements are met – implementation of effective signal separation in the receiver and high accuracy measurements of signal parameters.

Effective signal separation is done based on the applied modulation methods [5].

Noise immunity is an important component for providing high accuracy measurements of signal parameters. For noise immunity organization special radio signal filters are applied in order to reduce the influence of thermal noise radiation of the Earth, planets, the Sun, stars and interstellar environment [6]. Applied frequency noise canceling algorithms include standard Bessel, Butterworth, Chebyshev, Kauer filters [7] and a modified low frequency filtering (LFF) algorithm. The algorithm is based on direct and inverse Fourier transform [8] introducing Euclidean metric for bandwidth determination. Bandwidth determination is based on an idea of signal discretization with following distance averaging among all point pairs and comparing the calculated mean distance with the distance between every pair of neighboring points. The distance  $d_{mid}$  between two neighboring points  $p^{i-1}$  and  $p^i$  ( $i$  – point number) is calculated according to formula (1), and condition (2) is checked:

$$d_{mid} = \frac{\sqrt{(p_1^1 - p_1^2)^2 + (p_2^1 - p_2^2)^2} + \dots + \sqrt{(p_1^n - p_1^{n-1})^2 + (p_2^n - p_2^{n-1})^2}}{n-1} = \frac{\sum_{i=1}^{n-1} \sqrt{\sum_{j=1}^2 (p_j^{i+1} - p_j^i)^2}}{n-1}, \quad (1)$$

where  $n$  – number of points,  $j$  – dimensionality,  $i$  – point number.

For high (low) frequency filters

$$\begin{cases} \text{if } d(p^i, p^{i+1}) - d_{mid} > (<) 0, \text{ then } d(p^i, p^{i+1}) \in w_{cutoff} \\ \text{else } d(p^i, p^{i+1}) \in w_{bandwidth} \end{cases}, \quad (2)$$

where  $w_{cutoff(bandwidth)}$  – cutoff band and bandwidth, respectively.

Conditions analysis of navigation signal propagation from NSC to tracking SC (SC in HEO-1) for the 10-day period (from 00:00:00 01.06.2016 to 00:00:00 11.06.2016, UTC time) is considered as a modeling example. Results regarding the influence of signal filtering algorithms on the conditions of NSC radio visibility are provided in Table 3.

**Table 3.** Results of signal filtering algorithm implementation.

SC in HEO	Filtering methods (filters)	Number of radio visibility sessions	Maximum/minimum number of radio visible satellites	Mean number of radio visible satellites
HEO-1	Bessel	1162	17/1	6.70
	Butterworth	1168	17/1	6.73
	Chebyshev	1144	16/1	6.34
	Kauer	1179	17/1	6.87
	Modified LFF	1190	18/1	7.07
	Without signal filtering	1138	16/0	6.25

Algorithms share the same initial parameters (4<sup>th</sup> order filters). Based on the results, the best radio visibility indicators for SC in HEO-1 correspond to using the modified LFF algorithm.

## 5. Conclusion

In this work the calculation of theoretically optimal antenna system directivity patterns was done for SC in HEO and analysis of influence of the developed data processing algorithms on NSC radio visibility conditions was conducted. It was proposed to use the modified LFF algorithm for filtering a signal transferred from NSC to SC in HEO, which showed the best results of all implemented filtering algorithms in case of SC in HEO-1.

Obtained results may be helpful for receiving antenna design of SC in HEO.

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