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Use of GNSS for autonomous navigation on medium Earth orbits

Use of GNSS for space navigation is relatively cheap solution that provides a possibility to find your own position, improved recovery time after manoeuvres for spacecraft and satellites, etc. Medium Earth orbits are not that interesting for business; but they still have their own use. The research provides information about availability of different satellite constellations and some data on accuracy of navigation solution for the medium Earth orbits.

How GNSS works for space users.

Determination of the coordinates of a space vehicle is important for different operations in space (docking, movement to desired orbit, recovery after manoeuvres, etc), or that would be relevant in the near future (with the removal of large orbit space debris and other operations). Even though satellite navigation systems are most effective on the Earth's surface so far, the question arises – how effective are they when moving away from Earth’s surface to the space service volume? As stated in interface control documents of GPS and GLONASS, these systems provide full coverage only up to 3000 km for GPS and up to 2000 km for GLONASS above Earth surface.

According to the same document, the GPS space service volume (SSV) lies between 3000 km and 36000 km. There is no performance standard for it as of yet, but the possibility for navigation is actively researched upon.

The coordinates, velocity and time of satellite navigation systems in the medium Earth orbits is performed in the radio navigation field, which is formed by radio signals emitted by satellites. To determine the coordinates in three-dimensional space it is necessary to simultaneously receive signals from at least four satellites (the use of multiple constellations might require more satellites for position fix).

The navigation satellites are located at the height of about 20 000 kilometers above Earth that is within the limits of the investigated area. Therefore, we can only see limited amount of navigation satellites in direct view on the altitudes below 20 000 km and actually no satellites above. To allow the space navigation the so-called off-nadir satellites can be used. They broadcast signal from beyond the Earth’s limb. The details are given in Fig. 1.

Fig. 1 depicts how the off-nadir satellites broadcast their signals into space and has several important regions. First is the main lobe region, it corresponds to the signals that are broadcast through the main lobe of the satellite antenna radiation pattern and contain most of the signal strength. They are between the ± 13.8° to ± 23°, as a part of the signal is shadowed by the Earth. The side lobes region corresponds to the signals broadcast through the side lobes. They feature weak feed and initially were considered parasitic. Their use actually allowed to obtain passable results on higher orbits. They lie between ± 30° and ± 60°, though the signal strength is not guaranteed.

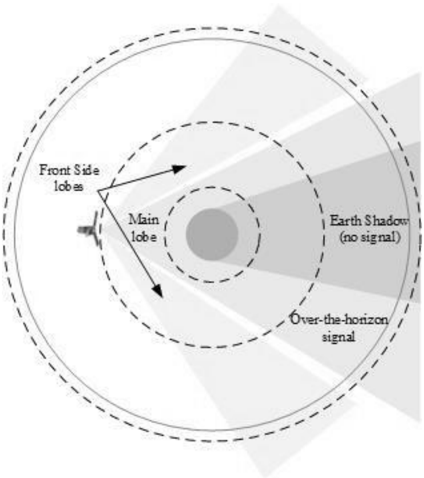

Fig. 1. Propagation of the signal broadcast by off-nadir satellites

Situation on medium Earth orbits

For working with satellite navigation systems in space a software product was created in Matlab, which allows simulating the situation in the given point of near-Earth space and defining the available satellites, dilution of precision (DOP) and other parameters.

The simulation goes through following steps in order to obtain the results:

1. Record, download or generate a Yuma-format almanac that is valid for the time set in the research.
2. Input data for the selected position in the near-Earth space and set other simulation parameters (chosen GNSS constellations, statistical data, constants, other parameters).
3. Extract the almanac data and calculate the satellite ephemeris and parameters for the given time interval.
4. Find which satellites are “seen” from the given position and their “source” (main lobe or the side lobe signal).
5. Calculate the DOP factors that influence the coordinate determination accuracy.
6. Add the errors from normal distribution with given sigma in the measured pseudorange and calculate statistical data.
7. Provide results and graphics.

For the given research the points above Kiev were chosen and with a step of 1000 km starting from 3000 km and up to 36 000 km the simulation was performed. The time moment is the same for all the points in the simulation. The first set of results is provided for GPS system with main lobes only, the second set features the addition of side lobe signals.

Experimental results

The experiment results are organized into tables for convenience reasons. Table 1 illustrates the results of the use of GPS with the signals that are broadcast from main lobes only. The results range from 3000 km to 36 000 km with a 1000 km step. Table 2 provides similar information but with the addition of side lobe signals.

Table 1.

Results of the simulation of main lobe signals for different altitudes

Altitude km	Sat. Nu.	RMS, m	GDOP	Altitude km	Sat. Nu.	RMS, m	GDOP
3000	25	0,5958144	0,65	20000	1	NaN	NaN
4000	25	0,5981717	0,65	21000	1	NaN	NaN
5000	17	0,8115733	0,85	22000	1	NaN	NaN
6000	12	0,9541329	1,04	23000	1	NaN	NaN
7000	8	1,4487548	1,56	24000	1	NaN	NaN
8000	7	2,0098304	2,21	25000	0	NaN	NaN
9000	5	3,9335593	4,40	26000	0	NaN	NaN
10000	5	3,7325644	4,50	27000	1	NaN	NaN
11000	5	4,1918383	4,61	28000	1	NaN	NaN
12000	4	4,2266051	4,86	29000	1	NaN	NaN
13000	4	4,4914005	5,00	30000	1	NaN	NaN
14000	4	4,7184398	5,14	31000	1	NaN	NaN
15000	3	NaN	NaN	32000	1	NaN	NaN
16000	2	NaN	NaN	33000	2	NaN	NaN
17000	1	NaN	NaN	34000	2	NaN	NaN
18000	1	NaN	NaN	35000	2	NaN	NaN
19000	1	NaN	NaN	36000	2	NaN	NaN

The results from Table 1 clearly indicate that the main lobe signals are clearly not enough for consistent navigation in higher near-Earth orbits. Column one indicates the investigated altitude, while column 2 shows the number of visible satellites. The root-mean square (RMS) error illustrates the error of the user position estimations. The RMS of the error injected to the calculated pseudoranges was 1.7 m, as there are no ionospheric or multipath errors and the main contributor is distance. The solar radiation is not taken into account in the model. It should also be noted that this is a combined error for all three coordinates' estimation. The fourth column provides the information about the Geometrical dilution of precision (GDOP) that affects the accuracy of user coordinates estimation. Other columns repeat the four mentioned above to save space.

When the spacecraft moves through lower levels it can still access the satellites that are in direct view and the satellites' geometry allows finding a lot of off-nadir signals, but as one fly to the higher altitudes the situation changes. Starting from about 5000 km only 3 satellites can be seen in direct view. The number of direct view satellites further decreases to 1 at 7000 km (the only satellite which is directly above the given point) and even it disappears at 15 000 km. The number of the off-nadir satellites also decreases. There were 7 satellites available at 7000 km, but their number decreased to only 2 at 15 000 km.

The accuracy of coordinate determination is highly affected by the number of visible satellites. Therefore, the RMS also decreases with the decrease of satellite number. It starts from about 0.6 m on 3000 km orbit and decreases to 0.8 m at 5000 km, 1.45 m at 7000 km. The worst value of 4.71 m is obtained at 14 000 km, and the real-time navigation solution is unavailable further. It is quite common for only 1 or 2 satellites to be available on higher Earth orbits. The GDOP factor scales in a similar pattern from 0.65 on 3000 km and up to 5.14 on 14000 km.

It should be noted that it is still possible to obtain 4 satellites on higher Earth orbits (especially on geostationary one), but it is a rare occasion and requires significant observation time to find at least several occasions.

Table 2.

Results of the simulation of main lobe and side lobes signals for different altitudes

Altitude km	Sat. Nu.	RMS, m	GDOP	Altitude km	Sat. Nu.	RMS, m	GDOP
3000	25	0,5873438	0,65	20000	17	2,44841	3,10
4000	25	0,5938636	0,66	21000	16	3,02274	4,06
5000	17	0,8075414	0,85	22000	17	3,02800	4,09
6000	12	0,9979992	1,04	23000	17	3,27271	4,32
7000	10	1,1564275	1,29	24000	17	3,27676	4,57
8000	16	0,7871602	0,85	25000	16	4,28884	5,53
9000	15	0,7872386	0,88	26000	14	5,89136	8,95
10000	19	0,7194890	0,78	27000	15	4,83596	6,87
11000	22	0,6788834	0,75	28000	15	5,19556	7,20
12000	23	0,6960661	0,75	29000	15	5,34248	7,53
13000	23	0,6914038	0,77	30000	14	5,90983	8,37
14000	25	0,6870121	0,76	31000	15	6,01649	8,26
15000	24	0,7980708	0,95	32000	15	6,19354	8,61
16000	25	0,7315174	0,82	33000	16	5,21163	7,56
17000	23	0,8000663	0,95	34000	17	5,96475	7,74
18000	22	0,9150437	1,04	35000	17	5,71200	8,05
19000	18	1,9772337	2,55	36000	16	5,99137	8,72

The results from Table 2 indicate a significant improvement as compared to the results of the main lobe only research. Though the lower altitudes are not affected by the presence of side lobe signals due to their interesting geometry (check Fig. 1). The number of visible satellites is same as in Table 1 for up to 6 000 km inclusive. From there on the solution is affected by the side lobe signals. The addition of side lobes has allowed to obtain solution for the entire range of altitudes.

Moreover, the accuracy has significantly improved. The RMS error is only 0.687 m at the altitude of 14 000 km, while the RMS error is equal to 4.72 m for a corresponding altitude in Table 1. It is interesting to note that DOP factors significantly increase with the increase of altitude, which is a bad sign. If we compare the values of GDOP on the altitudes of 36000 km and 8000 km, we can see that the values of GDOP differ between each other by more than 10 times, which results in RMS errors of 5.99 m and 0.79 m for the respective altitudes. The number of visible satellites is 16 for both heights.

Conclusions

The research indicates that it is impossible to use the satellite navigation for medium Earth orbits if only the main lobe signals are used. There has to be another source of signals for them to work. In this research, the side lobe signals are used to enhance the performance of satellite navigation. They make it cheap and viable to employ this navigation type for the autonomous position determining in a spacecraft or the enhanced manoeuvre recovery, as satellite navigation only requires a sensitive on-board receiver.

References

1. FAA "Global Positioning System Standard Positioning Service Performance Standard", 4th edition, - September, 2008. - 160 p.
2. Valeriy Konin, Fedir Shyshkov, Olexiy Pogurelskiy, Estimation of Coordinates on Geostationary Orbit by Using GNSS Signals, Proc. Of the 3rd Radar Methods and Remote Sensing Symposium (RMSW 2016), 27-28 September, 2016, Kyiv, Ukraine, - pp.32-35 – Way of Access : DOI: 10.1109/RMSW.2016.7778544
3. V. Konin., A. Pogurelskiy., F. Shyshkov, "GNSS availability on geostationary orbit," 5-th international conference «Space Technologies: Present and Future», Dnepropetrovsk, 19-21 May 2015, p. 145 - Way of Access: http://er.nau.edu.ua:8080/handle/NAU/25209
4. Konin, V. Autonomous navigation of service spacecrafts on geostationary orbit using GNSS signals / Valeriy Konin, Fedir Shyshkov // Radioelectronics and Communications Systems. – 2016. – Vol. 59, N 12. - P. 562-566. – Way of Access : DOI : 10.3103/S0735272716120049.
5. Konin, V. Model for navigation satellite availability on various orbits analysis / V. Konin., A. Pogurelskiy., F. Shyshkov // Proceedings, THE SIXTH World Con-gress. Aviation in the XXI- st Century. Safety in Aviation and Space Technologies, September 23–25, 2014 .– Kyiv, 2014. – V.2, – P.3.2.22 – 3.2.25 – Way of Access: http://er.nau.edu.ua:8080/handle/NAU/25239