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THE ADVANCED CONCEPT OF SMALL SATELLITE INTEGRATED NAVIGATION SYSTEM, BASED ON GPS/GLONASS TECHNIQUE*

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Abstract

The authors discuss a prospective approach to solution of the spacecraft navigational problem by an autonomous gyro-less navigation system. Its operation is based on use of an on-board GPS/GLONASS receiver as a primary source of navigational information, and payload earth observation camera and a magnetometer as auxiliary navigational sensors, and information fusion techniques and aimed at effective use of information from all the sources. The principles of GLONASS/GPS navigation, models and algorithms used for simulation of the navigation process are considered in detail. Accuracy estimations received as the result of Monte-Carlo simulation applied to TUD-Satellite demonstration mission are cited.

Key words: spacecraft autonomous navigation, gyro-less navigation, information fusion, GPS, GLONASS, landmark, magnetometer.

Introduction

During the next 10-15 years the number of LEO spacecraft will increase up to hundreds, primarily due to creation of LEO communication systems such as IRIDIUM, GLOBALSTAR or TELEDESIC. Support of such numerous constellations is a heavy burden on the ground control segment from both technical and financial points of view, so it is expedient to transfer solution of many tasks that are traditionally solved on the ground to the spacecraft on-board systems.

In this paper the authors consider a possible approach to solve on board one of such tasks, namely, the navigational one, i. e. the problem of determination of the spacecraft position, velocity, attitude and angular rate.

Obviously, on-board receivers of global satellite positioning systems such as American GPS and Russian GLONASS can solve the positioning problem. Besides, advanced receivers, such as the Russian device described in this paper, can use signals of both systems and determine not only spacecraft position and velocity, but also attitude and angular rate.

At the same time, long life times of the modern communication satellites call for increased reliability of navigational systems. Instead of traditional hardware redundancy, i. e. usage of several dedicated navigational devices (e. g. receivers), an alternative approach based on functional redundancy is suggested[2,6]. In accordance with this approach, a minimum hardware autonomous navigation system for low-earth orbiting spacecraft can be created using GPS/GLONASS receiver as the source of navigational information during the nominal operation and on-board earth observation camera and magnetometer, both installed on board as the secondary payload, for backup navigation. The fusion of these information sources is performed by advanced filtering and estimation methods.

Such an approach provides an adequately accurate and at the same time a cheap and reliable solution to the problem of spacecraft navigation: any single device (receiver or camera or magnetometer) can provide

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solution to the navigational problem, while necessary redundancy is provided by use of secondary payload, originally not assigned for navigational purposes.

The paper presents the overall system architecture with emphasis on the advanced GLONASS/GPS receiver and first performance results which have been derived for the TUD-Satellite demonstration mission[7] as the application reference by computer simulation of the navigation process.

Basic Navigational Techniques

GPS/GLONASS Navigation

GPS/GLONASS navigation is based on utilization of multi-channel GPS/GLONASS integrated receiver for solution of both orbit and attitude determination problems.

The main advantages of GPS/GLONASS navigation are:

- redundancy of involved navigational satellites belonging to both GPS and GLONASS constellations,
- absence of Selective Availability mode of operation for GLONASS navigation,
- more favorable (compared to GPS) observability of GLONASS satellites as applied to such reference missions as GLONASS, IRIDIUM, etc.

The main disadvantages are:

- necessity to have backup on-board navigation and attitude determination system to provide coarse position, velocity, and attitude estimations to obtain initial data for GPS/GLONASS attitude determination procedure,
- necessity to have on-board antenna system (3 or 4 antennae) and, therefore, 3 or 4 different receivers for attitude determination problem solution,
- influence of the small length of on-board antenna system baseline, of the satellite body distortion and of the multi-beam effect as unfavorable factors on solution of the attitude determination problem.

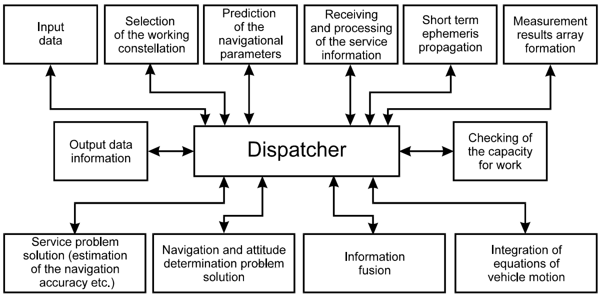

Fig. 1. Simplified diagram of the on-board GLONASS/GPS software arrangement

Algorithms for determination of position, velocity, and time are known very well nowadays and implemented in various space vehicles. That is why, below we will pay attention only to peculiarities of implementation of such algorithms.

It is known, that to solve the navigation problem it is necessary to perform the following actions:

- search of satellite signals,
- capture of signals,
- signals tracking,

and simultaneously to provide receiving and decoding of the service information. Besides, we have to compensate ionosphere refraction (for spacecraft applications) as well as to provide correction of the measurement results by correction of the time scale and frequency of on-board generator of each cooperating satellite.

Almanac data, also transmitted in the message, are used for both the working constellation selection and signal search and tracking. The position and velocity components of each navigation satellite at the measurement time instant are computed by short term propagation, using ephemeris information. To solve the navigational problem itself, various data processing algorithms can be used, such as Kalman filter or Least Square Method modifications.

All the above listed operations, which should be implemented during every single navigational session, can be provided by a complex set of subroutines (modules), illustrated in Fig. 1.

We will consider the problem of the satellite attitude determination as the problem of the antenna system baselines attitude determination with respect to the axes of the reference frame.

It is known that second differences of the pseudoranges of two navigational are functions of second differences of the carrier phases of signals from the mentioned satellites.

The specific feature of the phase differences measurement is restriction of the phase difference in the range $[0, 2\pi]$. To perform the measurement process it is necessary to develop so called counter (indicator) of the integers of the signal periods. This counter should indicate output +1 or -1, if the magnitude of the phase difference reaches the value 0 or 2π, correspondingly. This counter is in fact the essence of the attitude determination algorithm.

Backup (Landmark and Magnetometer) Navigation

Landmark navigation is based on comparison of the images obtained by the on-board Earth observation equipment (hereinafter called camera) and the images of the same areas of the Earth’s surface stored in the on-board computer.

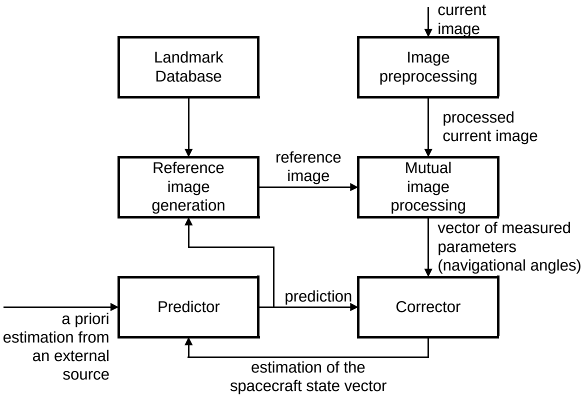

Fig. 2 Flowchart of landmark navigation

The basic principles of landmark navigation, its advantages and disadvantages are considered in detail in[5,6]. Briefly, the concept of landmark navigation consists of the following steps (see Fig. 2):

- On the ground, before the flight, a landmark database is formed.
- During the flight, current images (obtained by the camera) are formed periodically; reference images are generated using landmark database by the on-board computer for the same moments of time.
- The current and reference images are processed together to identify corresponding elements (landmarks); three «best» landmarks are chosen and their coordinates in the current image are determined.
- Navigational angles are formed based on the results of image processing; they are fed into Kalman-type filter along with current estimation of the spacecraft state vector and predicted values of the navigational angles to correct the state vector.

The measurement vector consists of nine angles:

- three angles between directions of the pairs of the lines-of-sight of the three landmarks used for position estimation only and do not change with any of the other components of the state vector.
- six angles (three pairs) characterizing the attitudes of the landmark lines-of-sight in the spacecraft body frame used for attitude estimation.

The principle of magnetometer navigation, based on comparison of the measured and reference values of the local magnetic field, is well known and described, for example, in [8,9].

Information fusion

In the considered gyro-less autonomous spacecraft navigation system the information fusion techniques are used for the following purposes [6]:

1. In the navigational system initialization mode the coarse estimation of the spacecraft state vector obtained using magnetometer and/or camera is used to resolve the initial ambiguity of attitude determination by GLONASS/GPS receiver.
2. In the nominal mode of operation the information from the receiver is used to calibrate the navigation algorithms, camera, and magnetometer.
3. In the backup mode of operation the navigational measurements performed by magnetometer and camera complement each other: camera provides more accurate data, whereas magnetometer provides more coarse data during the long intervals between measurements performed by camera.

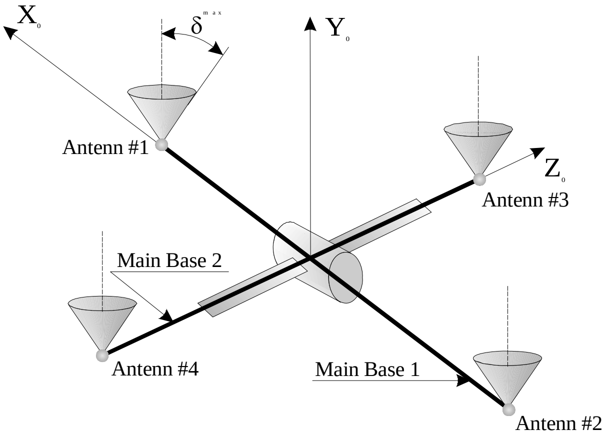

Fig. 3 Antennae arrangement

Simulation of the Prospective Navigation System Operation

The well known procedures are accepted to solve the navigation problem, including procedures of GPS/GLONASS constellation integrity analysis, optimization of cooperating satellites constellation, secondary data processing, etc.

Solution of satellite attitude determination problem is provided by processing of the carrier phase differences of the signal, received by antenna. The mentioned phase differences are measured based on the so called «main» antennae system bases (Fig. 3).

Least Mean Square method is used for processing of carrier phase differences in order to solve the attitude determination problem. It means, in particular, that all the phase differences, measured at the current time

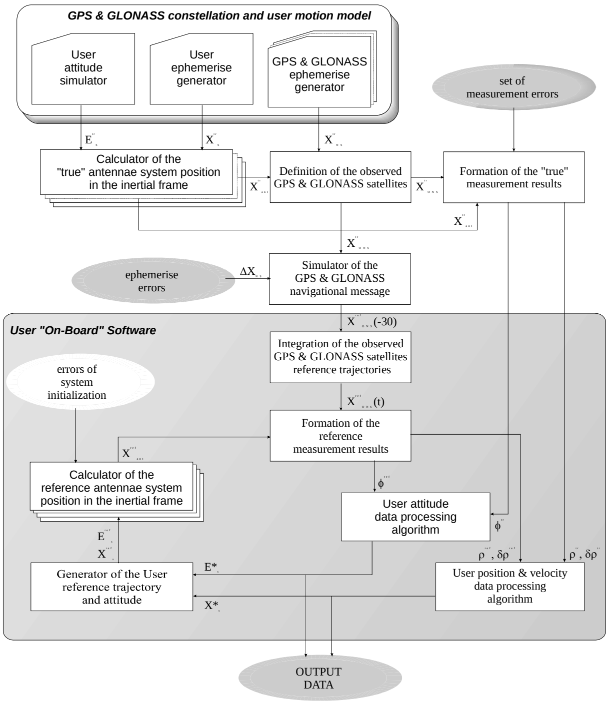

Fig. 4 Simplified diagram of simulation

instant using all the observed navigational satellites, are considered as a complete sample to be processed by the LMS method. As the result, it is not necessary to involve complete mathematical model of angular satellite motion in the attitude determination algorithm.

The simplified diagram of simulation is given in Fig. 4. The following notations are used in this figure:

X_S^{tr} is the vector of «true» TUD satellite position and velocity components in the absolute inertial frame (IF2000),

E_S^{tr} is the vector of «true» TUD satellite Euler angles,

X_{NS}^{tr} is the vector of «true» GLONASS and GPS satellites ephemerides,

X_{ant}^{tr} is the vector of «true» antenna position in the IF2000 frame (see below in detail),

X_{ONS}^{tr} is the vector of «true» observed navigational satellites (ONS) ephemerides,

ρ^{tr} is the vector of «true» pseudorange measurement results, obtained from the observed navigational satellites,

$\delta\rho^{tr}$ is the vector of «true» pseudorange rate measurement results, obtained from the observed navigational satellites,

Φ^{tr} is the vector of «true» carrier phase difference measurement results, calculated for the observed navigational satellites,

X_{ONS}^{ref} is the vector of observed navigational satellites ephemerides, which corresponds to the navigational message,

X_{NS}^{ref} is the vector of observed navigational satellites short term («reference») ephemerides, calculated by the satellite onboard computer,

X_S^{ref} is the user «reference» state vector, calculated by the onboard computer bases on the previous estimations,

E_S^{ref} is the vector of the «reference» satellite Euler angles, calculated by onboard computer based on the previous estimations and angular motion model,

X_{ant}^{ref} is the vector of the «reference» antenna position in the IF2000, calculated by onboard computer, using X_S^{ref} and E_S^{ref} data,

$\rho^{ref}, \delta\rho^{ref}, \varphi^{ref}$ are corresponding reference measurement data, generated based on the corresponding reference vectors $X_S^{ref}, X_{ant}^{ref}, E_S^{ref}, X_{ONS}^{ref}$.

E_S^{*}, X_S^{*} are the vectors of estimations of the user attitude, position and velocity.

To obtain the values of $X_S^{tr}, E_S^{tr}, X_{NS}^{tr}$, the most accurate and complete models of motion as well as high-accuracy integration method are used.

Mathematical Models and Algorithms

Let us emphasize, that for simulation of the considered navigation system one has to create the following mathematical models and algorithms:

- GLONASS and GPS constellation model;
- GLONASS and GPS satellite observability model;
- user orbital and angular motion models;
- navigational message and receiver antennae system models;
- algorithm of user position and velocity determination;
- algorithm of user attitude determination.

All the mentioned models have been created, considering wide set of uncontrollable factors and errors, such as GLONASS and GPS ephemerides maintenance systematic errors caused by the errors of orbit determination of the navigation satellites by the on-ground complex; pseudorange and pseudorange rate systematic and random measurement errors caused by ionosphere delay, receiver clock drift and internal receiver noise; carrier phase difference measurement systematic and random errors caused by multi-path phenomenon, receiver clock drift, internal receiver noise; systematic and random errors of system initialization caused by the errors of auxiliary sensors data.

A recursive Bayes algorithm (a modification of Kalman filtering) or the Least Mean Square algorithm has been used for user position and velocity determination. The latter has been used also for the user attitude determination.

As it was said above, two levels of the used models have been developed for simulation: the more accurate model and integration method for «true» ephemerides generation and simplified model and integration algorithm for simulation of both navigation messages and «onboard» short-term ephemerides generation.

Mathematical model of the navigational satellites motion

Firstly, let us pay attention to the «true» ephemerides generation technique. Below we turn our attention only to its main specific features.

The mathematical model of «true» ephemerides generation considers influence of the following uncontrollable factors (disturbances): force resulting from the Earth oblateness according to Cunningham expansion [3] till the 8th order, force resulting from Sun and Moon gravitational influence, aerodynamic drag force, force resulting form the solar pressure.

The highly accurate Dormand-Prince integration method [3] of the 5(4) order with automatically adjustable step has been used for computation GPS and GLONASS satellites «true» position and velocity, considering the above mentioned disturbances. To provide efficiency of obtained integration results utilization, one uses Chebyshev's polynomial approximation technique[3]. The order of polynomial was accepted equal to 16 and approximation interval has been accepted equal to 1000 sec.

The simplified model for simulation of both navigation messages and «onboard» short-term ephemerides generation (so called «reference» data) considers the force resulting from the Earth oblateness according to Cunningham expansion till the 2nd order and force resulting from Sun and Moon gravitational influence.

The standard Runge-Kutta integration method of the 2/6 rule with fixed step was used for computation of GPS and GLONASS satellites «reference» position and velocity, considering the above mentioned disturbances. To utilize the obtained integration results for «reference» ephemerides generation Chebyshev's polynomial approximation technique has been used as well.

To simulate the error of ephemerides maintenance one uses «true» ephemerides, corresponding to the closest half an hour, «distorted» by the additive random vector with zero mathematical expectation and diagonal covariance matrix with the following r.m.s. values:

$$\sigma_r = \sigma_l = \sigma_n = 10\text{m.}; \ \sigma_{\dot{r}} = \sigma_{\dot{l}} = \sigma_{\dot{n}} = 0.05\text{m/s},$$

where the *r, l, n* subscripts denote radial, tangential and normal directions correspondingly.

Mathematical model of the user satellite motion

Two levels of the models complexity have been used for simulation of the user motion: the more accurate models and integration method for «true» satellite position and velocity computation and simplified model and integration algorithm for the «reference» data generation by the «onboard» software. The highly accurate technique for the user position and velocity computation is the same as for the «true » GPS and GLONASS satellites ephemerides generation.

To use the obtained integration results for the user «true» ephemerides generation one uses Chebyshev's polynomial approximation technique. The order of polynomial is equal to 16 and approximation interval is equal to 500 sec.

The simplified «onboard» user motion model for the «reference» data performing considers the force resulting from the Earth oblateness according to Cunningham expansion till the 2nd order and the aerodynamic drag force.

The standard Runge-Kutta integration method of the 2/6 rule with fixed step is used for computation of the user «reference» position and velocity, considering the above mentioned disturbances. A priori data are used as initial conditions for the «onboard» equations of the user motion. Later the current estimations of position and velocity are used, when «**User position and velocity data processing algorithm**» unit is initialized.

The simplest model of the user angular motion was accepted as the «onboard» one due to LMS algorithm utilization in the «**User attitude data processing algorithm»** unit, namely:

$$\dot{E}_s^{ref} = 0, \ E_s^{ref} = \left(\vartheta \mid \psi \mid \gamma\right),$$

where υ, ψ, γ are pitch, yaw and roll correspondingly.

Mathematical models of navigational measurements

According to the accepted simulation technique there are the following two sorts of navigational measurement models: the models of the «true» measurements and the models of the «reference» measurements, used in the «onboard» software.

Mathematical models of the «true» measurements consider the following errors:

- systematic errors, considered as random variables formed by corresponding first-order shaping filters:
    - error caused by onboard user receiver clock drift,
    - error, caused by ionospheric delay,
    - error of the pseudorange rate measurement,
    - error, caused by multi-path phenomenon,
- random errors, considered as sequences of independent Gaussian random variables with zero mathematical expectation and fixed variances:
    - error caused by internal receiver noise,
    - error of the pseudorange rate measurement,
    - error, caused by internal receiver noise.

Algorithms of the user position and velocity determination

Two versions of the data processing algorithms can be utilized for the user position and velocity determination, namely a recursive Bayes algorithm, which is a modification of the Kalman filter, and the Least Mean Square algorithm of the complete sample processing.

The modification of the Kalman filtering algorithm has the following specific features. There are two cycles of algorithm operation: external and internal ones. The external cycle means enumeration of the navigation sessions, and internal cycle means enumeration of the observed navigational satellites during given navigation session. Thus, navigation session is the time instant of the receiving of the navigational messages from all the observed GPS and GLONASS satellites (taking into account the restriction on the elevation).

Algorithm of the TUD satellite attitude determination

This Least Mean Square algorithm also has two cycles (the internal and external ones), implemented in the same way, as for determination of the user position and velocity. The difference consists in the way of the observation matrix computation. In contrast to position and velocity determination LMS algorithm, here one computes the elements of the comprehensive observation matrix in respect to pitch, yaw and roll. Besides, for prediction of the Euler's angles estimations and covariance matrix for the next navigation session, the simplified model of the TUD satellite is used.

Simulation Results

Input Data for Simulation

The reference mission used during computer simulation of the navigational system is based on orbital characteristics of the TUD- Satellite [6]. This small (about 100 kg) satellite will be placed on a 500 km, 53^o circular orbit and will have no orbit control means. The attitude control system will be based on passive gravity gradient stabilization combined with active attitude stabilization and control using momentum wheel and magnetotorquers.

The simulation interval is equal to 6000 sec; this magnitude is approximately equal to the TUD satellite period of revolution. Mathematical model of the TUD satellite angular motion corresponds to [7].

The above mentioned five versions of GLONASS and GPS constellations are considered.

Errors of the TUD satellite position and velocity determination are:

- for GLONASS the r.m.s. error of the TUD satellite position is equal to 25 m; the r.m.s. error of its velocity is equal to 0,5 cm/sec,
- for GPS the r.m.s. error of the TUD satellite position is equal to 100 m; the r.m.s. error of its velocity is equal to 50 cm/sec (taking into account GPS C/A mode of operation).

Errors of carrier phase differences measurement:

- the r.m.s. error of the systematic error, caused by the multipath phenomenon is varied in the following way: 0.0033m, 0.005m, 0.01m, 0.033m, 0.05m;
- the r.m.s. error of the additive random noise is equal to 0.005m.

Description of Simulation Results

During the simulation of the user attitude determination process using GLONASS/GPS receiver, the influence of the following factors has been explored:

- various completeness of GLONASS and GPS navigation satellites constellation, namely: GLONASS only, GPS only, GLONASS+GPS, incomplete GLONASS only, incomplete GLONASS+GPS;
- different length of satellite antennae system base;
- different level of systematic errors.

All the obtained simulation results have been processed using Monte-Carlo technique.

Below one can see dependencies, which characterize influence of antenna system base length, observation conditions, GLONASS and GPS constellation completeness and systematic errors level on the accuracy of the TUD satellite attitude determination.

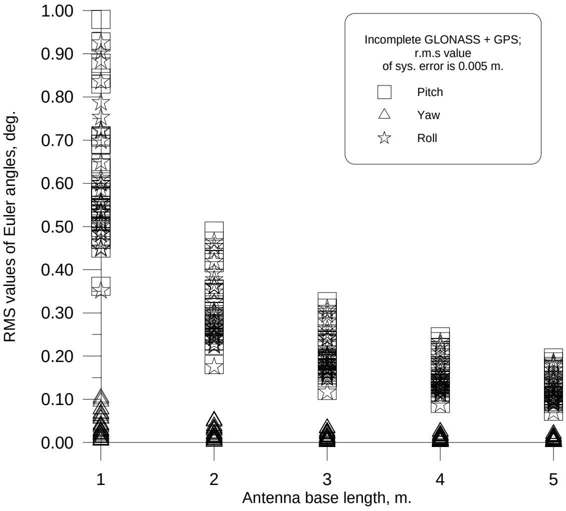

Fig. 5 Incomplete GLONASS+GPS

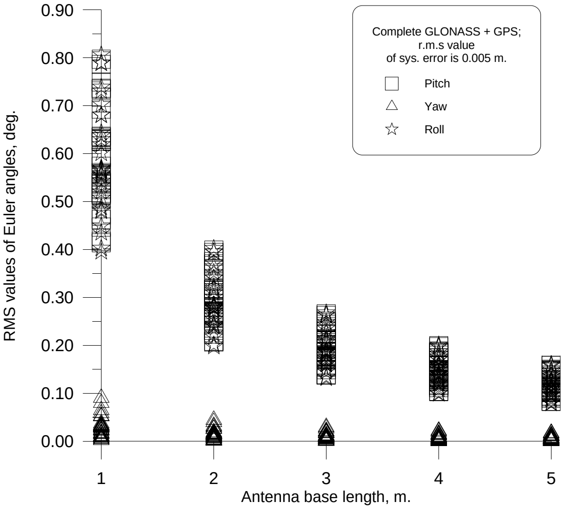

Fig. 6 Complete GLONASS+GPS

Main attention was paid to the influence of the antenna system base length. These results are demonstrated in Fig. 4 – 8. Each symbol on these figures corresponds to 30 samples of Monte-Carlo simulation. The magnitude of r.m.s. attitude for any fixed base length depends also on the observation condition and magnitude of systematic error, which is fixed and is equal to 0.005m.

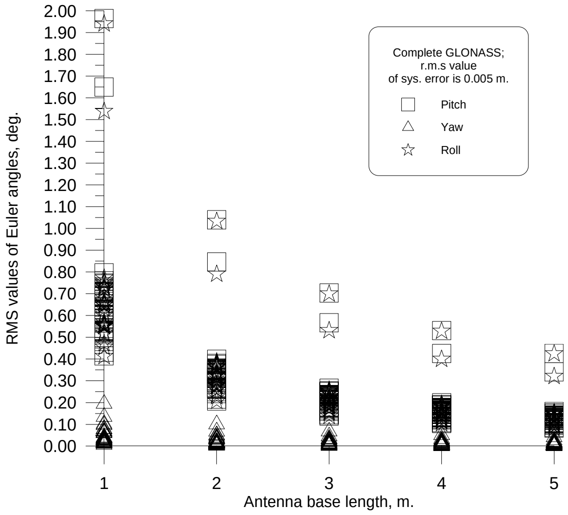

Fig. 7 Complete GLONASS

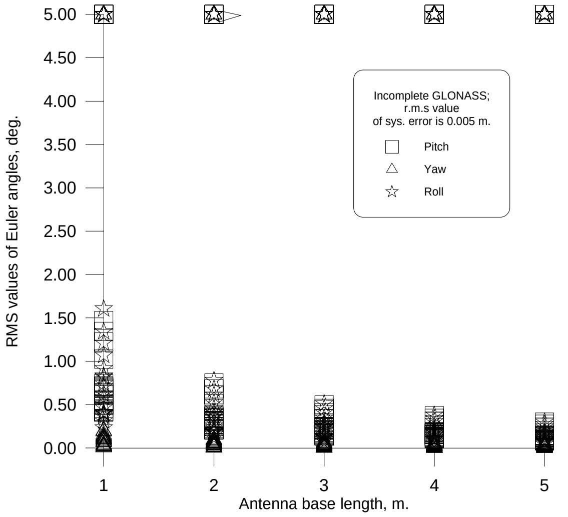

Fig. 8 Incomplete GLONASS

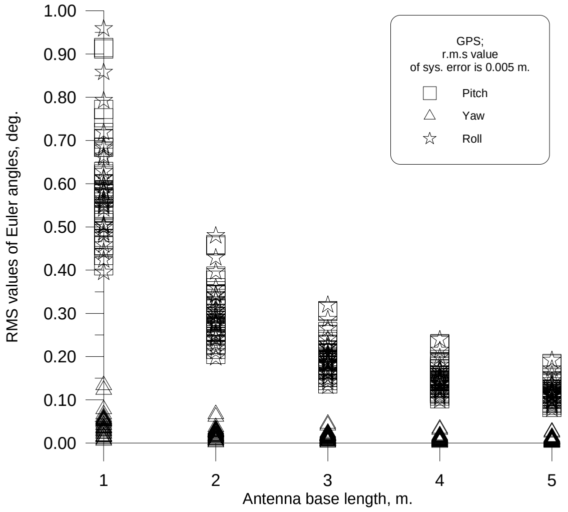

Fig. 9 GPS only

Accuracy of Navigation and Attitude Determination Provided by Auxiliary Sensors

The study has also demonstrated the efficiency of the suggested landmark navigation technique: the estimation process converges in a very wide scope of orbits, camera characteristics, and other parameters of the models. For the TUD-satellite reference mission the method provides solution to the navigational problem with maximum error not worse than 4 — 6 kilometers[1,4]. The attitude is determined with the maximum error not exceeding 1 degree (yaw) and 20 arc sec (pitch, roll). So, the accuracy of orbit determination is much worse that accuracy of GLONASS/GPS navigation, but the accuracy of attitude determination is comparable or even better; the latter fact can be effectively by information fusion.

It is a well known fact that magnetometer navigation provides accuracy of navigation with errors not exceeding 30-50 km and several degrees, correspondingly (see [9] and references in it); in other words, the accuracy is much worse that accuracy of GLONASS/GPS or landmark navigation. At the same time, magnetometer can provide estimation of the spacecraft space vector even when the initial estimation is very bad and at any moment of time. Hence, its data can be used for initialization of the navigational system and as a backup source of navigational information.

Conclusions

This article shows that autonomous spacecraft navigation system, fitting minimal hardware concept, based on use of on-board GPS/GLONASS receiver, earth observation camera and magnetometer, is very prospective for LEO satellites.

The authors are going to continue the research in the following main directions:

- further development of algorithms for attitude determination using the receiver and camera,
- design of information fusion algorithms,
- detailed performance evaluation considering enhances models of heterogeneous uncontrollable factors to obtain more justified numerical results.

Acknowledgments

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