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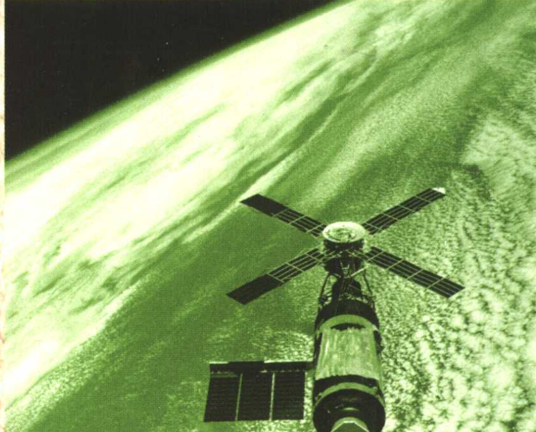
# 国际导航制导控制学术会议论文集

赵 琳◎主编



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# 国际导航制导控制学术会议论文集

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哈尔滨工程大学出版社

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本学术论文集收集了100多篇导航制导控制方面的优秀学术论文，内容包括航海航空导航，控制理论和应用，模拟系统的设计与实现。

本书可供相关专业的学者和专家们借鉴参考。

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* Paper unavailable at time of printing

# Simulation Software for a Low Cost Electronic Inertial Navigation System

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**ABSTRACT** This paper addresses the first step of a design sequence for inertial navigation systems: to design a generic and flexible simulator that will allow the simulation of different system's architecture scenarios. In order to realize fast prototyping systems, to take advantage of modular design and to allow rapid real-time testing, a Simulink© Navigation System Simulator (SNSS) has been developed. The SNSS is designed in several modules allowing point-wise improvements or modifications that do not affect the other modules. The aim of this first version of the simulator is to analyse the propagation of round-off errors in an ideal context. Major results have shown no significative effects of the simulator finite arithmetics on the accuracy of the solution. The SNSS will be a precious tool in the design of the innovative algorithm expected to be suitable for the use of MEMS inertial sensors in low cost navigation systems. Upon completion, this software will permit rapid prototyping and easy-to-use design for low cost GPS-aided electronic inertial navigation systems.

## 1. INTRODUCTION

For many years, low cost inertial navigation systems (INS) are subject of great interest. In the last decade, the development of Micro-Electro-Mechanical Systems (MEMS) has permitted mass production of devices, though reducing the cost of previously expensive sensors [1]. Applications for such systems are numerous and many researchers around the world are now spending efforts to integrate low cost and low precision sensors to INS (e.g. [2-5]). The 3D-ETSNAV research group, at the Ecole de technology superior is part of the challenge and works toward the integration of MEMS inertial sensors in a fully operational GPS-aided navigation system.

Simulation of aided-INS systems is mandatory prior to real implementation in order to validate the design [6]. Furthermore, numerical analysis of algorithms behavior is necessary since the highly non-linear equations governing the system prohibit extensive analytical analysis. Simulation package tools available until now to achieve this goal are Matlab script files (www.gpsoftnav.com). However, modular and easy graphical design allowed by Simulink© urged us to conceive a simulator based on their blockset, and new ones that has been created. Also, it will permit to do rapid real-time testing, which is a goal for the physical implementation. To our knowledge, only one simulator that uses Simulink© for INS budget error analysis has been already presented [7]. However, this simulator uses a flat earth hypothesis and neglects the earth rate and the transport rate in the computation of inertial measurements.

The SNSS is different in a few aspects. First, the measurement generation module takes into account all aspects that might influence its behavior. Also, this module includes a block function for the gravity model that permits the improvement of the gravity model accuracy independently of the other modules. On this aspect, in order to simulate the inertial measurement with high precision, the gravity model will at least include non-spherical terms. Also, the simulator allows the user to model the dynamic response of the sensors, add noise and simulate any specific characteristic of the sensor. Another interesting aspect of the SNSS resides in the simulation of geometrical configuration of sensors that permits redundancy analysis. Finally, the modularity of the simulator will allow the direct real-time testing of a previously simulated navigation algorithm. This will reduce significantly the time needed to design a low cost INS.

The first section will introduce the basic mathematics about cinematic that constitute the core of measurements and trajectory generation. Then, the software architecture will be presented and the functionality of each module will be described. Finally, a brief numerical analysis will be performed in order to appreciate the propagation of round-off computation errors.

## 2. MATHEMATICS BACKGROUND FOR MEASUREMENTS GENERATION

This first section introduces the mathematical basics in order to evaluate sensors measurements: rate gyros and accelerometers; and to determine some kinematic variables from the desired trajectory. The following frame are used:

- the earth-centered inertial (ECI) frame (i);
- the earth-centered earth-fixed (ECEF) frame (e);
- the local vertical (NED) frame (v);
- the mobile frame (m).

To mitigate the complexity of mathematical expressions, the following conventions are used. The vector notation $[{}^{a}X_{b}]_{c}$ is read as follow: the vectored kinematic variable *X* of the frame *b* w.r.t. the frame *a*, measured with respect to (w.r.t.) the frame *c*. The rotation matrix from frame *b* to frame *a* is given by ${}^{a}R_{b}$. The Euler angle (roll pitch and yaw) are respectively represented by $(\phi,\theta,\psi)$ while the longitude/latitude pair is represented by $(\lambda,\varphi)$. One dot over a variable means its first time derivative, while two dots correspond to its second time derivative. Also, the anti-symmetric matrix of a vector $X = [x_1\ x_2\ x_3]^T$ is expressed by $S\{X\}$.

$$S\{X\} = \begin{pmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{pmatrix} \quad (2.1)$$

### *2.1 Rotation rate measurement*

The rate gyro is measuring the angular speed of the sensor frame w.r.t. to an inertial frame. This angular rate can be decomposed into several intermediate ones that are more commom: the earth rate, the transport rate and the angular rate of the sensor frame w.r.t. the local frame, all of those measured in the sensor frame [8, 9]. These three components are respectively expressed in equation 2.2. Equations 2.3 and 2.4 give the details of each components. All of the variables are known or can be obtained by the trajectory generation module. Figure 2.1 shows the SNSS implementation of rotation rate generation (at the top).

$$[{}^{i}\Omega_{m}]_{m} = {}^{m}R_{e}[{}^{i}\Omega_{e}]_{e} + {}^{m}R[{}^{e}\Omega_{v}]_{e} + [{}^{v}\Omega_{m}]_{m} \quad (2.2)$$

$$[{}^{i}\Omega_{e}]_{e} = \begin{pmatrix} 0 \\ 0 \\ \omega_T \end{pmatrix} \ ; \ [{}^{v}\Omega_{m}]_{m} = \begin{pmatrix} \dot{\phi} \\ 0 \\ 0 \end{pmatrix} + {}^{m}R_{v}\begin{pmatrix} 0 \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} \quad (2.3)$$

$$[{}^{e}\Omega_{v}]_{e} = \begin{pmatrix} 0 \\ 0 \\ \dot{\lambda} \end{pmatrix} + {}^{e}R_{v}\begin{pmatrix} 0 \\ -\dot{\varphi} \\ 0 \end{pmatrix} = \begin{pmatrix} \dot{\varphi}\ s\lambda \\ -\dot{\varphi}\ c\lambda \\ \dot{\lambda} \end{pmatrix} \quad (2.4)$$

### *2.2 Specific force measurement*

The acceleration, or to be more rigorous the specific force, can be calculated by inverting the fundamental equation of navigation and isolating the needed variable [10]. Measured in the earth frame, the solution is given at equation 2.5, where ${}^{e}P_{m}$ is the position of the mobile w.r.t the ECEF frame and $g({}^{e}P_{m})$ is the gravity model.

$$[{}^{i}A_{m}]_{m} = {}^{m}R_{e}\begin{pmatrix} {}^{e}\ddot{P}_{m} + 2S\{[{}^{i}\Omega_{e}]_{e}\}{}^{e}\dot{P}_{m} + \\ S\{[{}^{i}\Omega_{e}]_{e}\}S\{[{}^{i}\Omega_{e}]_{e}\}{}^{e}P_{m} - \\ g({}^{e}P_{m}) \end{pmatrix} \quad (2.5)$$

Even if some variables can be obtained from the trajectory generator, the gravity acceleration vector has to be modeled. In order to conceive a simulator as close as possible to the reality, and in order to analyze the effect of different gravity models in navigation algorithms, the model of the gravity field for measurements generation has to be accurate. Hence, the use of non-spherical terms added to the spherical ones in the gravity model (or the use of a complex gravity representation) is mandatory. Figure 2.1 also shows the SNSS implementation of specific forces generation (at the bottom).

### *2.3 Trajectory generation*

The trajectory generation module was implemented with high precautions because it is the one that gives the kinematic variables information to the other blocks. The generation of the trajectory is based on the acceleration of the mobile w.r.t. the ECEF frame but measured in the local frame. With this information and its mathematical integration, and by use of the relation expressed at equation 2.6, one can obtain the acceleration of the mobile w.r.t. the ECEF frame, but now measured in the ECEF frame. Given this acceleration, the speed and the position w.r.t. the ECEF frame are easily obtained and the latitude/longitude (LATLONG) position can be computed.

$$[{}^{e}\dot{V}_{m}]_{e} = S\{[{}^{e}\Omega_{v}]_{e}\}\,{}^{e}R_{v}[{}^{e}V_{m}]_{v} + {}^{e}R_{v}[{}^{e}\dot{V}_{m}]_{v} \quad (2.6)$$

Rotation matrices required by the previous equations are computed with variables obtained so far. The rotation matrix from the local frame to the earth frame (in equation 2.3) uses the LATLONG position. On another hand, the rotation matrix from rotation matrix and another one obtained by use of Euler angles. Figure 2.2 shows the SNSS implementation of the trajectory generation.

## 3. SOFTWARE ARCHITECTURE

As said previously, the software is designed in a modular perspective to allow easy reconfiguration of its different components. Figure 3.1 gives an overview of the different modules and an explanation follows for each of them.

### *3.1 Trajectory and measurements generation*

Up to now, the trajectory generation is based on acceleration profile of the mobile w.r.t. the earth frame and measured in the local frame. A future add-on will consist in designing a graphical user interface allowing the user to "draw" a trajectory in a 3D map by means of via-points, as C. Eck did in is work [7] or input the software with real 3D trajectory scenarios.

It is worth nothing that the measurement generation module is not exactly the simulation of the inertial sensors, but the computation of the equivalent rotational rate and specific forces the mobile is subjected to based on the desired trajectory.

### *3.2 Sensor model*

The output of this module is the simulated sensor measurements based on the ideal "measure" given by the previous module. It will include many sensor characteristics and geometrical configurations. The sensor model is of great importance in the SNSS because a sensitivity analysis with respect to sensor characteristics and geometrical configurations will be performed on the navigation algorithm. Sensor will be modeled by using the following characteristic errors expressed in their stochastic form (but are not limited to):

- ✓ bias errors;
- ✓ scale factor errors;
- ✓ misalignment;
- ✓ quantization.

### *3.3 Navigation algorithm*

In this version of the simulator, the navigation algorithm that has been implemented is purely analytical and did not make use of any filter. It was simply designed for testing the measurement generation module and to analyze the propagation of round-off errors through the simulator modules in an ideal context. Equations 3.1 and 3.2 correspond to the analytical navigation equations in the ECEF frame and figure 3.2 gives an overview of its implementation.

$$ {}^e\dot{R}_m = -S\{[{}^i\Omega_e]_e\}{}^eR_m + {}^eR_m S\{[{}^i\Omega_m]_m\} \tag{3.1} $$

$$ {}^e\ddot{P}_m = \begin{pmatrix} -2S\{[{}^i\Omega_e]_e\}{}^e\dot{P}_m - \\ S\{[{}^i\Omega_e]_e\}S\{[{}^i\Omega_e]_e\}{}^eP_m + \\ g({}^eP_m) + {}^eR_m[{}^iA_m]_m \end{pmatrix} \tag{3.2} $$

## 4. PRELIMINARY RESULTS

The results presented here concern the numerical stability of the simulator, e.g. to see the quantization effect or how much finite arithmetic influence the propagation of errors in the navigation solution. The trajectory used to generate the data is a cruise flight (fixed altitude of 100m) with a constant velocity (30 m/s) for one hour from a fixed coordinate point to another one. The rotation rate subsystem will be investigated first, and secondly, the translational performance will be presented.

### *4.1 Rotation rate numerical accuracy*

The accuracy of the rotational rate blockset calculation is evaluated simply by comparing elements of the rotational matrix generated by the trajectory module and the ones computed by the solution of equation 3.1. As figure 4.1 shows, the error propagation is quite small compared to the absolute value and seems to be relatively constant, since there is no feedback use of information in the process. Hence, the propagation of computation error in this block is not significant and will not modify the results in future analysis.

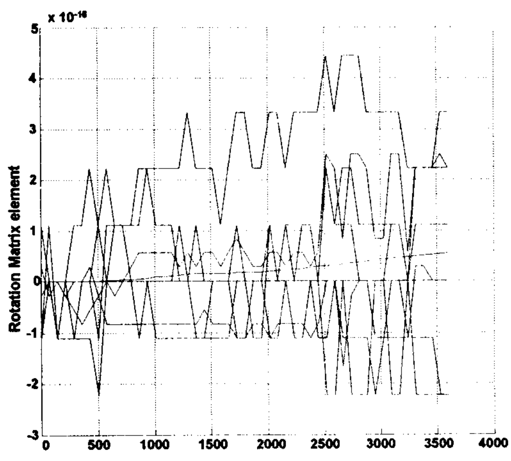


Figure 4.1 Error propagation of elements of the rotation matrix ${}^eR_m$

### *4.2 Translation dynamics numerical accuracy*

The error analysis for this block was performed in several stages, because of the feedback nature of its solution. First, all the information needed to solve the equation 3.2 is given by the trajectory and measurement generators. Then, the cinematic variables of the mobile frame w.r.t. the ECEF frame, measured in the ECEF frame was compared with the generated one. Figure 4.2 gives the results obtained from the simulation. It shows a high stability of the error on the acceleration solution when connected in an opened loop. Obviously, the speed and the position errors grow as time goes by, since integrators accumulate the previous errors.

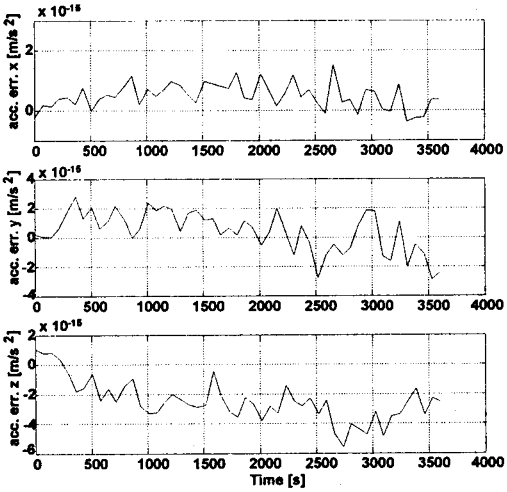


Figure 4.2 Error propagation in acceleration $[^e a_m]_e$: opened loop

Of course, this will have an influence on the solution of translational equation using feedback of the kinematic variable and with the computation of gravity acceleration based on the position of the mobile, as it will be shown next.

The next simulation involves the feedback of all the information, as a differential equation is normally solved. As figure 4.3 demonstrates, the propagation of error increases with a feedback of information compared with the previous simulation, which was expected. The magnitude of the position error due to computation after one hour is not very significative. However, great care will have to be taken so that further analysis will not be biased by long term simulation computation error drift.

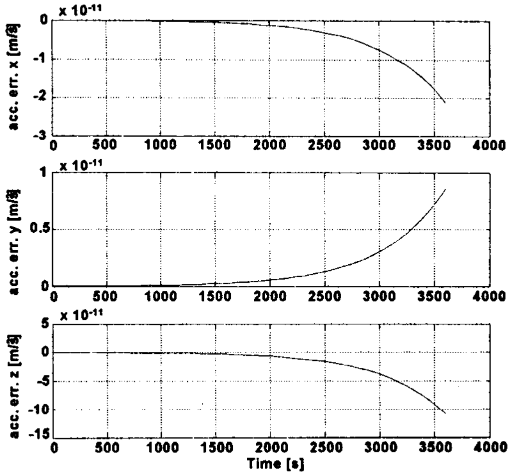


Figure 4.3 Error propagation in acceleration $[^e a_m]_e$: closed loop

## CONCLUSION

This paper exposed the design of a Simulink© Navigation System Simulator (SNSS). The use of a simulator is mandatory in order to design a suitable algorithm that takes into account the specificity of Low cost sensors like MEMS inertial sensors. The tools available since now have not been found adequate for our needs and urged the development of a modular and easy to reconfigure simulator. With the SNSS, many sensitivity analysis will be performed and among them: sensor noises and response bandwidth, geometrical configuration of the sensors, relevance of precise gravity model, refresh rate of external signals, etc. Another interesting feature of the simulator is the fast-prototyping capability due to its modular design and the use of the Real-Time Workshop of Simulink©. Finally, the simulator will be refined during the project, as new experiments will be done. At the end of the development phase, the SNSS will constitute a powerful tool to do rapid designs and prototyping of Low-Cost INS.

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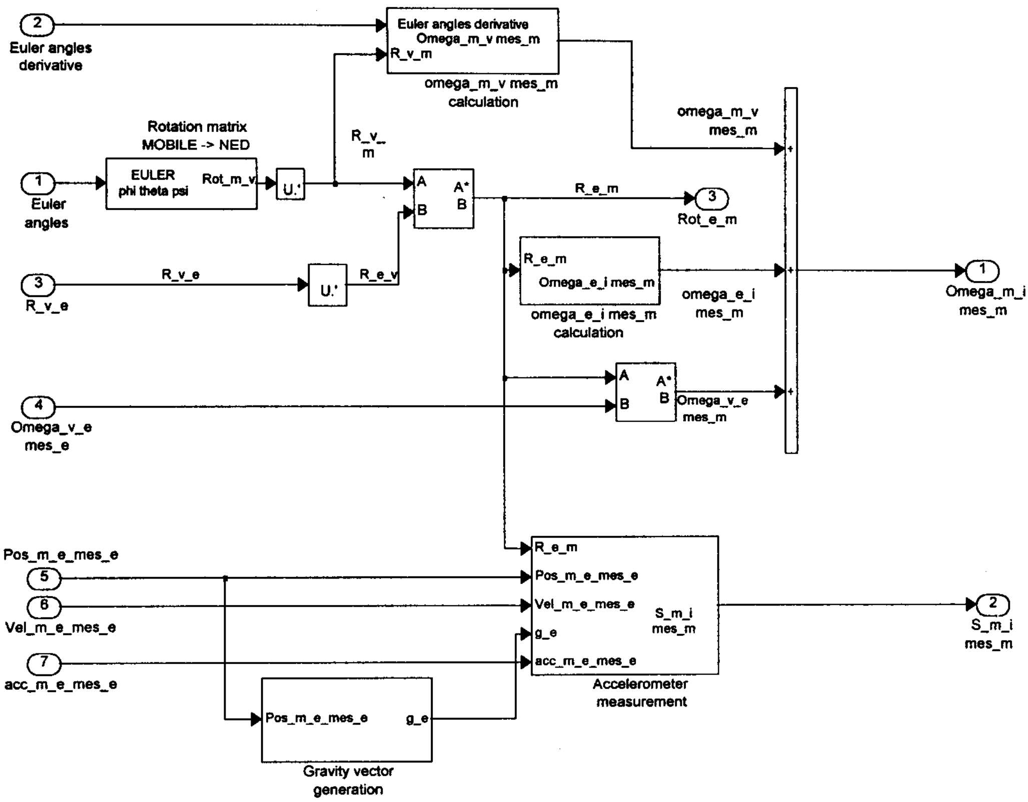


Figure 2.1 Measurement generation module

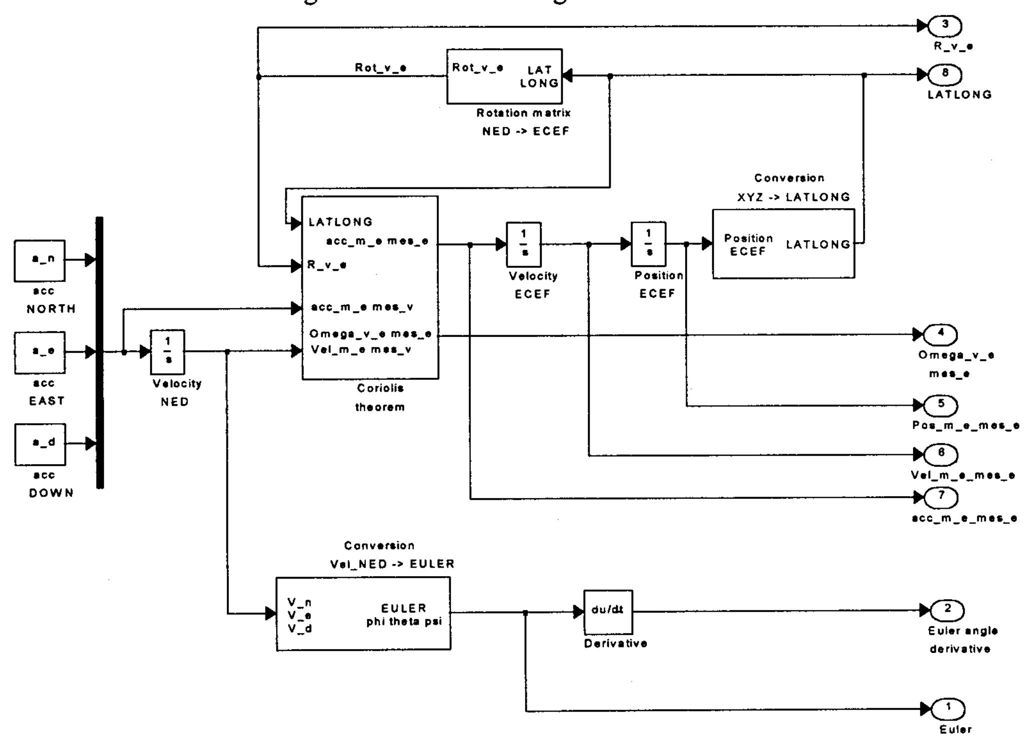


Figure 2.2 Trajectory generation module