International Journal of Engineering
Journal Homepage: www.ije.ir

TECHNICAL NOTE

Earth's Magnetic Field for Spacecraft Attitude Control Applications

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P A P E R I N F O

Paper history:
Received 06 November 2013
Accepted in revised form 29 January2015

Keywords:
Earth's Magnetic Field
Spacecraft Attitude Control
Linear and Nonlinear Transformation
Orbital Frame
Body Frame

A B S T R A C T

In this paper the earth's magnetic field is simulated precisely while the intensity and direction of the field are verified with one of the standard references for selected points on the earth and the results are compared with some low-order models. In another simulation, the complete model is compared with a common approximate model. The magnetic field in orbital frame is described and to employ earth's magnetic field in spacecraft attitude control applications, it is transferred into the spacecraft body frame. Transformation between orbital frame and body frame can be linear or nonlinear; the validity of linear transformation is investigated regarding various attitude angles. The divergence plots and the plot and table of error percentage illustrate the result based on the defined acceptable error.

doi: *10.5829/idosi.ije.2015.28.05b.01*

1. INTRODUCTION

Nowadays, space missions are operational; either, in near earth, or deep space. This is achieved with advances in optimal trajectory techniques which meet the energy resources limitations for such missions [1]. These limits have also leaded us to use the available natural resources such as magnetic field. The magnetic field has been an interesting research topic in several aspects of science. For instance, its effects on fluids are numerically investigated [2, 3].

In recent decades, employing satellites in low earth orbit (LEO) has an increasing trend. The LEO satellites functionally experience the earth's magnetic field more than other ones. The earth's magnetic field is used to control the attitude of spacecraft by the interaction between the earth's magnetic field and the magnetic dipoles generated in the satellite body. Initially, in order to use this phenomenon, the intensity and the direction of the earth's magnetic field is obtained. One of the best ways to model is utilizing the harmonic coefficients and the earth's magnetic field mathematical model. In this study, the earth's magnetic field is modeled based on the 11th generation of the IGRF (International Geomagnetic Reference Field) coefficients and the results are verified with the reference standard. In the next step, to utilize the earth magnetic field in the attitude control of a spacecraft, it is necessary to transform the magnetic field into the spacecraft body frame. The transformation between orbital and body frames may be linear or nonlinear. In the following, based on the comparison of the results of linear and nonlinear transformation, the validity of linear transformation is studied regarding spacecraft attitude angles.

A rigid spacecraft can be described as a system of particles that their relative distances are fixed during the time. The spacecraft attitude equation is as follows [4].

$$\mathbf{T} = \dot{\mathbf{h}}_I = \dot{\mathbf{h}}_B + \boldsymbol{\omega} \times \mathbf{h}_B. \quad (1)$$

where $\mathbf{T}$ denotes the external moments vector, $\mathbf{h}$ the angular momentum vector, and $\boldsymbol{\omega}$ the angular velocity vector. The subscripts I and B refer to the inertial frame and body frame, respectively. In derivation of the spacecraft attitude equations, external moments are shown as the sum of disturbance $(\mathbf{T_d})$ and control $(\mathbf{T_c})$ torques: $\mathbf{T} = \mathbf{T_c} + \mathbf{T_d}$ and the total angular momentum as the sum of rigid body $(\mathbf{h})$ and momentum exchange devices $(\mathbf{h}_w)$ angular momentum: $\mathbf{h}_B = \mathbf{h} + \mathbf{h}_w$.

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One of the conventional methods in satellite attitude control is to use magnetic actuators [5-7]. Magnetic actuators operate based on the interaction between current-driven coils and the geomagnetic field. Due to sharp decrease in earth magnetic field intensity regarding altitude rise, low earth orbits are emphasized in this work. The magnetic control torque ($\mathbf{T}_c = \mathbf{T}_{mag}$) is produced by cross product of the magnetic dipole ($\mathbf{m}$) and the earth's magnetic field vector ($\mathbf{B}$) [4, 8].

$$\mathbf{T}_c = \mathbf{T}_{mag} = \mathbf{m} \times \mathbf{B} \tag{2}$$

2. MODELLING THE EARTH'S MAGNETIC FIELD

The existence of the earth's magnetic field was known in China more than 1000 years ago. The first study of this subject refers to Gilbert in 1600. He indicated that the earth's magnetic field is a dipole that its axis is alongside with the axis of rotation of the earth. Changes in the main magnetic field with time, known as secular variation, have been recognized since Henry Gellibrand compared magnetic declination measurement he made in London in 1643 with measurements made by Gunter and Borough 12 and 54 years earlier, respectively [9].

In this work the earth's magnetic field is modeled employing the earth's potential function and the 11th generation of the IGRF coefficients. One of the best references verifies the accuracy of the results. The dominant portion of the earth's magnetic field can be represented as the gradient of a scalar potential function, $B = -\nabla V$. V can conveniently be represented by a series of spherical harmonies [8]:

$$V(r, long, colat) = a\sum_{n=1}^{N}(\frac{a}{r})^{n+1}\sum_{m=0}^{n}[g_n^m \cos(mlong) + h_n^m \sin(mlong)]P_n^m(colat) \tag{3}$$

where a is the equatorial radius of the earth, g_n^m and h_n^m are Gaussian coefficients, r, $long$ and $colat$ are the geocentric distance, co-elevation and East longitude from Greenwich which define any point in the space respectively. The Gaussian coefficients are determined by a least square fit on observations of the geomagnetic field. These measurements include the direction and magnitude of the earth's magnetic field in lots of points on the earth.

Generally, the global observatory network collects magnetic data only at a limited number of non-uniform distributed points. The progress in technology has provided the opportunity to obtain high quality information by launching satellites that carry vector magnetometers. The first mission defined for this task was the MAGSAT satellite that operated from November 1979 to May 1980. Although this mission provided the most accurate model of the earth's magnetic field at that time span, it did not last long enough to provide an accurate model of the secular variation. Before the successful mission of the Orsted satellite that provides data of a similar quality to MAGSAT allowing a second highly accurate figure of the earth's magnetic field, the geomagnetic community had waited for 20 years [10].

In its simplified forms, Equation (3) is called dipole when N=1, quadrupole when N=2 and octupole when N=3. Obviously more coefficients lead to more accurate model. The 11th generation of IGRF coefficients that accepts dates in the range 1900 to 2020 whose 'N' is equal to 13[1] . Because of the conservative nature of the magnetic field $\nabla \times B = 0$, the earth's magnetic field in spherical coordinates is obtained by the gradient of the potential function in (3), as following:

$$B_r = \sum_{n=1}^{K}(\frac{a}{r})^{n+2}(n+1)\sum_{m=0}^{n}\left[g_n^m \cos(mlong) + h_n^m \sin(mlong)\right]P_n^m(colat), \tag{4}$$

$$B_\theta = B_{colat} = -\sum_{n=1}^{K}(\frac{a}{r})^{n+2}\sum_{m=0}^{n}\left[g_n^m \cos(mlong) + h_n^m \sin(mlong)\right]\frac{\partial P_n^m(colat)}{\partial colat}, \tag{5}$$

$$B_\phi = B_{long} = -\frac{1}{\sin(colat)}\sum_{n=1}^{K}(\frac{a}{r})^{n+2}\sum_{m=0}^{n}\left[-mg_n^m \sin(mlong) + mh_n^m \cos(mlong)\right]P_n^m(colat). \tag{6}$$

where $P_n^m(colat)$ and $\frac{\partial P_n^m(colat)}{\partial colat}$ are associated Lagrange functions and their derivatives.

The recursive formulas for the Gaussian normalized associated Legendre polynomials and their derivatives are as follows (Equations (7) and (8)) [8].

$$\begin{aligned}
&P^{0,0} = 1\\
&P^{n,n} = \sin colat P^{n-1,n}\\
&P^{n,m} = \cos colat P^{n-1,m} - K^{n,m}P^{n-2,m}\\
&K^{n,m} = 0 \qquad n = 1\\
&K^{n,m} = \frac{(n-1)^2 - m^2}{(2n-1)(2n-3)} \qquad n > 1
\end{aligned} \tag{7}$$

$$\begin{aligned}
&\frac{\partial P^{0,0}}{\partial long} = 0\\
&\frac{\partial P^{n,n}}{\partial long} = \sin colat \frac{\partial P^{n-1,n-1}}{\partial long} + \cos colat P^{n-1,n-1}\\
&\frac{\partial P^{n,m}}{\partial long} = \cos colat \frac{\partial P^{n-1,m}}{\partial colat} - \sin colat P^{n-1,m}\\
&-K^{n,m}P^{n-2,m}\frac{\partial P^{n-2,m}}{\partial colat}
\end{aligned} \tag{8}$$

Since associated Legendre polynomial ($P_{n,m}$) is displayed in the Gaussian normalized form ($P^{n,m}$), the $S_{n,m}$ (Equation (9)) is used to calculate the Gaussian normalized form of Gaussian coefficients ($g^{n,m}, h^{n,m}$) as well.

[1]http://www.geomag.bgs.ac.uk/data_service/models_compass/igrf.html

$$S_{n,m}=\left[\frac{(2-\delta_m^0)(n-m)!}{(n+m)!}\right]^{1/2}\frac{(2n-1)!}{(n-m)!} \tag{9}$$

The Kronecker delta is defined as $\delta_i^j=1$ if $i=j$, and $\delta_i^j=0$, otherwise. Using mathematical induction,it is possible to derive the following recursion relation for $S_{n,m}$ as Equation (10).

$$\begin{aligned}&S_{0,0}=1\\&S_{n,0}=S_{n-1,0}\left(\frac{2n-1}{n}\right)\quad n\geq 1\\&S_{n,m}=S_{n,m-1}\sqrt{\frac{(n-m+1)(\delta_m^1+1)}{n+m}}\quad m\geq 1\end{aligned} \tag{10}$$

The factor $S_{n,m}$ is independent of r, $long$ and $colat$ and so must be calculated only once. Thus, we define Equation (11).

$$\begin{aligned}g^{n,m}&\equiv S_{n,m}g_n^m\\h^{n,m}&\equiv S_{n,m}h_n^m\end{aligned} \tag{11}$$

Using the above relations, the field is calculated as follows:

$$\begin{aligned}&B_r=\sum_{n=1}^{K}\left(\frac{a}{r}\right)^{n+2}(n+1)\sum_{m=0}^{n}\left[g^{n,m}\cos(mlong)+h^{n,m}\sin(mlong)\right]P^{n,m}(colat),\\&B_\theta=B_{colat}=\\&-\sum_{n=1}^{K}\left(\frac{a}{r}\right)^{n+2}\sum_{m=0}^{n}\left[g^{n,m}\cos(mlong)+h^{n,m}\sin(mlong)\right]\frac{\partial P^{n,m}(colat)}{\partial colat},\\&B_\phi=B_{long}=\\&-\frac{1}{\sin(colat)}\sum_{n=1}^{K}\left(\frac{a}{r}\right)^{n+2}\sum_{m=0}^{n}\left[-mg^{n,m}\sin(mlong)+mh^{n,m}\cos(mlong)\right]P^{n,m}(colat).\end{aligned} \tag{12}$$

The spherical coordinates (r,θ,ϕ), which is called local tangent plane coordinate system is very similar to NED (North-East-Down) coordinates.

3. TRANSFORMATION OF THE EARTH'S MAGNETIC FIELD FROM LOCAL TANGENT PLANE COORDINATE TO BODY FRAME

The magnetic field literature normally refers to three components consisting of North, East and Down (nadir relative to the earth). These components are obtained from Equation (13).

$$\begin{aligned}B_N&=-B_\theta\cos\varepsilon-B_r\sin\varepsilon,\\B_E&=B_\phi,\\B_D&=B_\theta\sin\varepsilon-B_r\cos\varepsilon.\end{aligned} \tag{13}$$

where $\varepsilon\equiv\lambda-\delta<0.2^o$ and λ is the geodetic latitude and $\delta\equiv 90-lat$ is the declination.

In order to use the earth's magnetic in attitude control applications, the filed in body frame is needed.(see Equation (2)). As the first step, the earth's magnetic field in local tangent plane coordinates is transformed to the fixed earth inertial coordinates utilizing Equation (14).

$$\begin{aligned}&B_x^I=(B_r\cos\delta+B_\theta\sin\delta)\cos\alpha-B_\phi\sin\alpha,\\&B_y^I=(B_r\cos\delta+B_\theta\sin\delta)\sin\alpha+B_\phi\cos\alpha,\\&B_z^I=B_r\sin\delta-B_\theta\cos\delta,\\&\delta=90-colat,\alpha=long+\theta_g.\end{aligned} \tag{14}$$

where B_r, B_θ and B_ϕ are field components in spherical coordinates. δ and θ_g indicate declination and celestial time in Greenwich. The next step is to transform the magnetic field to the orbital frame using Equation (15).

$$\begin{aligned}&B_x^O=(-s\Theta c\Omega-c\Omega c\,i\,s\Omega)(B_r\cos\delta\cos\alpha+B_\theta\sin\delta\cos\alpha-B_\phi\sin\alpha)\\&+(-s\Theta s\Omega+c\Theta c\,i\,c\Omega)(B_r\cos\delta\sin\alpha+B_\theta\sin\delta\sin\alpha+B_\phi\cos\alpha)\\&+c\Theta s\,i(B_r\sin\delta-B_\theta\cos\delta)\\&B_y^O=(-s\,i\,s\Omega)(B_r\cos\delta\cos\alpha+B_\theta\sin\delta\cos\alpha-B_\phi\sin\alpha)\\&+(s\,i\,c\Omega)(B_r\cos\delta\sin\alpha+B_\theta\sin\delta\sin\alpha+B_\phi\cos\alpha)\\&-c\,i(B_r\sin\delta-B_\theta\cos\delta)\\&B_z^O=(-c\Theta c\Omega+s\Theta c\,i\,s\Omega)(B_r\cos\delta\cos\alpha+B_\theta\sin\delta\cos\alpha-B_\phi\sin\alpha)\\&+(-c\Theta s\Omega-s\Theta c\,i\,c\Omega)(B_r\cos\delta\sin\alpha+B_\theta\sin\delta\sin\alpha+B_\phi\cos\alpha)\\&-s\Theta s\,i(B_r\sin\delta-B_\theta\cos\delta)\end{aligned} \tag{15}$$

Θ, Ω and i are the orbital parameters. Θ is true anomaly, Ω and i show the right ascension of the ascending node and inclination respectively. s and c denote sine and cosine. Finally, transforming the magnetic field to the satellite body frame would be as Equation (16).

$$\begin{aligned}B_{NLx}^B&=\mathrm{c}\psi\,\mathrm{c}\theta B_x^O+(\mathrm{c}\psi\,\mathrm{s}\theta\mathrm{s}\phi-\mathrm{s}\psi\,\mathrm{c}\phi)B_y^O+(\mathrm{c}\psi\,\mathrm{c}\phi\mathrm{s}\theta+\mathrm{s}\psi\,\mathrm{s}\phi)B_z^O\\B_{NLy}^B&=\mathrm{s}\psi\,\mathrm{c}\theta B_x^O+(\mathrm{s}\psi\,\mathrm{s}\theta\mathrm{s}\phi+\mathrm{c}\psi\,\mathrm{c}\phi)B_y^O+(\mathrm{s}\psi\,\mathrm{s}\theta\mathrm{c}\phi-\mathrm{c}\psi\,\mathrm{s}\phi)B_z^O\\B_{NLz}^B&=-\mathrm{s}\theta B_x^O+\mathrm{c}\theta\mathrm{s}\phi B_y^O+\mathrm{c}\theta\mathrm{c}\phi B_z^O\end{aligned} \tag{16}$$

ϕ,θ,ψ indicate roll, pitch and yaw angles respectively.

Equation (16) shows the nonlinear matrix transformation from the orbital frame to the body frame. Assuming small Euler angles, the cosine is approximately equal to 1 and the sine is approximated by the value of the angles in radians, the equation is linearized as Equation (17).

$$\begin{aligned}B_{Lx}^B&=B_x^O-\mathrm{s}\psi\,B_y^O+\theta B_z^O\\B_{Ly}^B&=\psi B_x^O+B_y^O-\phi B_z^O\\B_{Lz}^B&=-\theta B_x^O+\phi B_y^O+B_z^O\end{aligned} \tag{17}$$

As it will be shown in the next section, the "small angle" definition, however usually seems a general definition, it is strongly dependent on the desired accuracy of the mission. Therefore, its upper bound value should be investigated in any specific case.

4. SIMULATIONS AND RESULTS

A MATLAB code has been developed by the authors in order to model the earth's magnetic field. In the first step, the code results in zero altitude on some points on the earth are compared with the BGS (British Geological Survey) results. The results are found satisfactory enough to be employed in attitude control issues.The results for London in Table 1 indicate that the error is less than two percent.

According to the table, the results are accurate enough. In Figure 1 the North component of the earth magnetic field are compared using four different models: dipole, quadrupole, octupole and the model based on the 11th generation of IGRF coefficients. In this figure, the positive association between the number of coefficients and the accuracy of the results is clearly visible.

As it is mentioned, the earth's magnetic field has to be expressed in body frame to be used in attitude control problems. Figure 2 shows the earth's magnetic field components in the orbital frame for a circular orbit with 500 km altitude and polar inclination.

One of the most popular approximate models of the Earth magnetic field is a dipole approximation of it, that when coupled with the assumptions of no Earth rotation and no orbit precession, yields to the following periodic model in orbital frame [11].

$$\begin{bmatrix} b_1(t) \\ b_2(t) \\ b_3(t) \end{bmatrix} = \frac{\mu_f}{a^3} \begin{bmatrix} \cos\omega_o t \sin i_m \\ -\cos i_m \\ 2\sin\omega_o t \sin i_m \end{bmatrix} \tag{18}$$

TABLE 1. The BGS and our code results for the earth's magnetic field and the error percentage, for London.

London	BGS results (NanoTesla)	Our code results (NanoTesla)	Error Percentage
B_{North}	19364	19074	1.50%
B_{Earth}	-558	-565.6	1.36%
B_{Down}	44571	44604	0.07%
$\|B\|$	48599	48514	0.17%

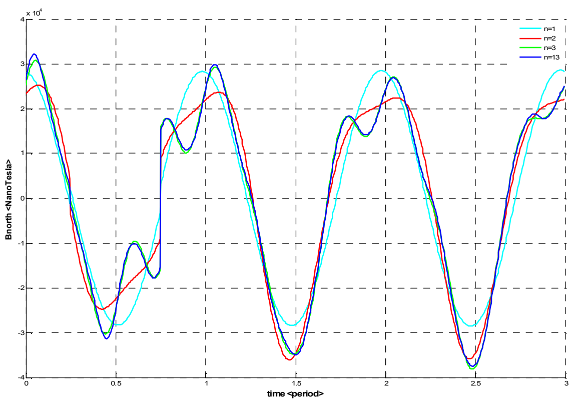

Figure 1. The north component of the earth's magnetic field based on dipole, quadrupole, octupole models and the 11thgeneration of IGRF in three orbital periods.

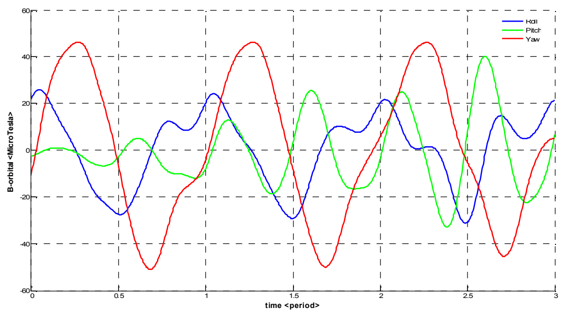

Figure 2. The earth's magnetic field components in the orbital frame in three orbital periods for a polar orbit.

In the Equation (18) i_m is the inclination of the spacecraft's orbit respect to the magnetic equator and a is the semi-major axis. The field's dipole strength is $\mu_f = 7.9\times10^{15}\ Wb-m$. Here we use $i_m = i + 11.4^o$ as the spacecraft's inclination relative to the magnetic equator.

Figure 3 shows a comparison between the results of the Equation (18) and the results of our code in orbital frame for an orbit with i=60 in 500km altitude.

In the next step the earth magnetic field in the body frame of the spacecraft is simulated. According to Equations (16) and (17), there are two transformations in order to transform the magnetic field from orbital frame to the body frame. Figure 4 shows the magnetic field intensity in the satellite body frame utilizing linear transformation.

In order to study the divergence of the magnetic field using linear approximation from the nonlinear transformation, a specific point in orbit with various attitude angles from 0^o to 30^o is considered. The results of magnetic field intensity error in body frame are shown for linear and nonlinear transformation in roll, pitch and yaw angles in Figure 5. Table 2 indicates the error percentage in three principal angles regarding various attitude axes. Equation (19) is used to calculate the error percentage of linearization.

$$Error = \frac{\left|B^{NL}_{Roll/Pitch/Yaw} - B^{L}_{Roll/Pitch/Yaw}\right|}{\left|B^{NL}_{Roll/Pitch/Yaw}\right|}\times 100. \tag{19}$$

Now, according to these results, it is possible to determine the border of validity of the linear transformation for this mission based on the desired accuracy. Based on Figure 5, it is clear that when the acceptable error for the mission is definedat about 10%, the upper bound of the attitude angle to be used in linear transformation is about 22^o on roll axis, 14^o on pitch axis and 15^o on yaw axis. Based on Table 2, for 10% acceptable error the average attitude angle on all three axes should not exceed 16^o. It means that when the defined desired accuracy for the mission is about 10 percent utilizing the linearization transformation is not valid for the attitude angles greater than 16^o. In this way, it is possible to find the upper bound of the “small angle” definition for any specific case. It should be mentioned that the validity of the “small angle” depends on the orbit properties and the defined acceptable error for any case.

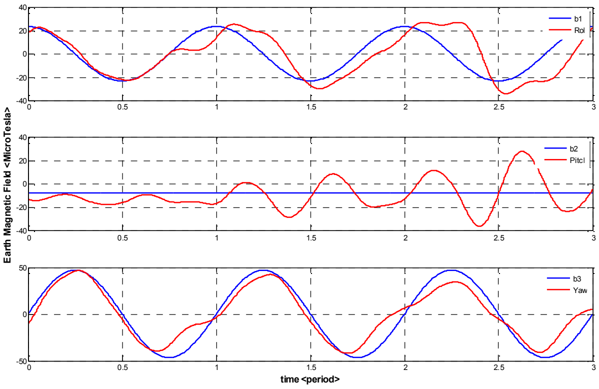

Figure 3. Comparison between the results of Equation (18) and the results of our code in orbital frame for an orbit with i=60 in 500km altitude.

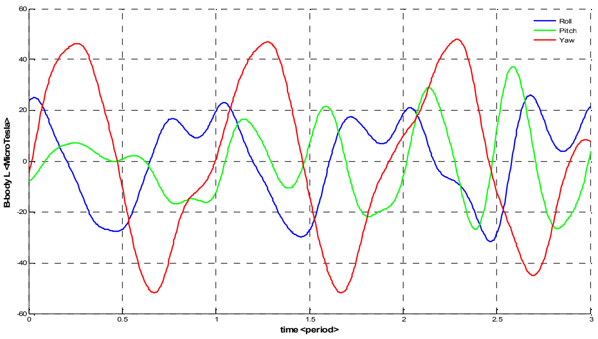

Figure 4. The earth magnetic field components in the body frame for 10^o attitude angle, utilizing linear transformation, three orbital periods.

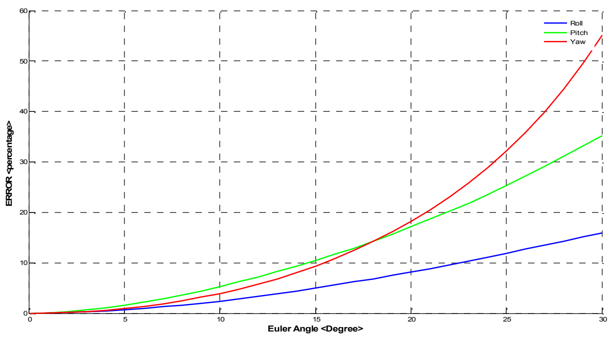

Figure 5. The error percentage of magnetic field components using linear transformation relative to nonlinear, regarding attitude angles.

TABLE 2. The error percentage of magnetic field components using linear transformation relative to nonlinear

	Error Percentage			
Attitude Angle	**Roll**	**Pitch**	**Yaw**	**Average**
1	0.03	0.08	0.037	0.05
5	0.67	1.59	0.95	1.07
10	2.42	5.26	3.94	3.87
15	4.98	10.46	9.40	8.28
20	8.18	17.11	18.23	14.51
25	11.88	25.33	32.20	23.14
30	15.98	35.30	55.15	35.48

5. CONCLUSION

Utilizing magnetic torque for spacecraft attitude control is a common way since the actuator is light, non-expensive and relatively easy to use. The contribution of this paper is to simulate the earth’s magnetic field precisely and to study the accuracy of some common approximate models as well. In addition, utilizing the earth’s magnetic field as a way for spacecraft attitude control and its considerations, such as using different transformations, are investigated. In order to apply this torque, the earth’s magnetic field has to be modeled accurately. In this study, the 11^{th} generation of IGRF coefficients is used to simulate the earth’s magnetic field, and the results are verified with one of the standard references. For comparing the trend of accuracy of different models with various orders, the simulation in orbital frame has been done for dipole, quadrapole and octupole models and the complete model. Another comparison has been made between a well-known dipole model and our developed code. In the next step, the earth’s magnetic field is transformed into the body coordinates of the spacecraft in order to be used in attitude control problems. The transformation from orbital frame to body frame can be either linear or nonlinear. Here both of them are simulated and the validity of linear transformation is investigated regarding the attitude angles. In addition, utilizing these simulations and considering the defined acceptable error for any mission makes it possible to define the upper limit of the “small angle” term. Notice that for any specific case, based on the orbital parameters and the desired accuracy, it is important to determine the small angle term by simulating and determining the validity of the linear transformation. Moreover, it has been shown that the error percentage of linear transformation has a rising tendency regarding the increase in attitude angles.

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PAPER INFO

Paper history:
Received 06 November 2013
Accepted in revised form 29 January 2015

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چکیده

در این مقاله میدان مغناطیسی زمین با دقت بالا شبیه‌سازی شده است. شدت و جهت میدان شبیه‌سازی شده با مقایسه با یک مرجع استاندارد برای نقاطی روی زمین اعتبارسنجی گردیده است. نتایج با چند مدل ساده شده و درجه پایین از جمله مدل دوقطبی شناخته شده مقایسه شدهاست. میدان مغناطیسی در دستگاه مداری بیان شده و سپس برای کاربرد در کنترل وضعیت به دستگاه بدنی فضاپیما انتقال داده شده است. این انتقال را می‌توان به دو صورت خطی و غیرخطی انجام داد. اعتبار مدل خطی برای زوایای وضعیت مختلف مورد بررسی قرار گرفته است. نتایج با توجه به میزان خطای مورد قبول به صورت نمودار واگرایی و جدول خطا ارائه گردیده است.

doi*: 10.5829/idosi.ije.2015.28.05b.01*