Geomagnetic Models at Low Earth Orbit and Their Use in Attitude Determination

Demet Cilden Guler, Zerefsan Kaymaz, Chingiz Hajiyev
Faculty of Aeronautics and Astronautics
Istanbul Technical University
Istanbul, Turkey
cilden@itu.edu.tr, zerefsan@itu.edu.tr, cingiz@itu.edu.tr

Abstract— **In this study, three geomagnetic field models, T89, CHAOS-6 and IGRF-12 models are compared at LEO orbit altitudes with the satellite observations. Comparisons between the models and with the observations are made using the total magnetic field and the components during the geomagnetically disturbed and quiet times. Main interest is to see how the angle between the modelled and observed magnetic field vectors changes. The differences are important since satellite's attitude determination system strongly depends on the angle. Effects of geomagnetic activity on the angle is investigated using geomagnetic activity index and the position of the satellite which are inputs to the models. Comparisons are made between the models using root mean square error analysis. Differences between the model magnetic fields and those of observed are seen to increase when the geomagnetic activity occurs. We discuss the implications of these differences on the satellite attitude determination system.**

Keywords— Earth's magnetic field; IGRF; CHAOS; T89; satellite attitude determination; magnetospheric substorms.

I. Introduction

Magnetometers are common attitude determination sensors for small satellites at low Earth orbit; therefore, magnetic field model of the Earth is necessary to estimate the satellite's attitude angles. The difference in the components of the magnetic field vectors -mostly used as a unit vector. Therefore, the angle between them (model and measurement data) affects the estimation accuracy of the satellite's attitude. In this study, geomagnetic field models are compared with satellite magnetic field observations in order to evaluate the models using the magnetometer results with high accuracy. For attitude determination system, International Geomagnetic Reference Field (IGRF) model is used in most of the cases but the difference between the sensor and model increases when the geomagnetic activity occurs. Hence, several models including the empirical ones using the external variations in the Earth's geomagnetic field resulting from the solar wind and interplanetary magnetic field are of great importance in the determination of the satellite's attitude correctly [1].

The most commonly used geomagnetic field model IGRF to find out the magnetic fields in the near-Earth space environment has a history that goes back 1900s. IGRF takes into account the internal part of the geomagnetic field of the Earth. The model is revised every five years and released by the International Association of Geomagnetism and Aeronomy (IAGA). The last generation (12th) of IGRF is released in December 2014 [2]. The other model, T89 is developed by Tsyganenko [3] which is an empirical model based on large satellite data and gives a model of the magnetosphere under the different geomagneticaaly diturbed conditions. In addition to the main field (internal) given by IGRF, T89 includes external magnetic field that arises as a result of magnetosphere solar wind interaction. The last model we investigate is the CHAOS model. The authors call their model CHAOS (the CHAMP, Ørsted and SAC-C model of Earth's magnetic field) owing to the unpredictable and chaotic nature of the Earth's magnetic field [4]. In the original version of the CHAOS, the near-Earth magnetic field model is derived using more than 6.5 years of high-precision geomagnetic field measurements from the three satellites taken between March 1999 and December 2005[4].

IGRF model describes the internal part of the geomagnetic field [2], while CHAOS-6 and T89 (Tsyganenko 1989 model), include simple parameterizations of the external magnetic fields from different magnetospheric sources superimposed on the internal geomagnetic field. Satellite magnetometers measure the total geomagnetic field with the disturbance fields added on the main geomagnetic field. Therefore, the differences between the satellite magnetometer data and those magnetic fields predicted by the geomagnetic models that model the main geomagnetic field, i.e. IGRF, will occur. These differences eventually will be propagated on the angle between the magnetic field vectors from the model and the magnetometer and will affect the satellite's attitude determination system. Therefore, it is important to see how well the geomagnetic models represent the satellite magnetometer data and consequently how much the external fields cause deviations in the angle used for the satellite's attitude.

In this study, to search for the effects of the external field, which increases during the geomagnetic activity, on the satellite's attitude, the geomagnetic models are evaluated at the satellite's position at LEO orbit during the selected days of geomagnetic activity. The comparisons are made in two ways: model-to-model and model-to-observation comparisons under various geomagnetic activity levels. Here, we present our initial results from a case study based on these comparisons and discuss their implications from the satellite attitude perspective.

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II. Geomagnetic Field Models

A. IGRF (International Geomagnetic Reference Field) Model

IGRF model includes series of the spherical harmonics at N=13th degree that are updated every 5 year. (1) gives the expansion with the coefficients. The inputs (r,θ,ϕ,t) are the radial distance (km) from the centre of the Earth, co-latitude (deg), longitude (deg) that come from the satellite position at the chosen time (t). The global variables (g and h) are Gauss coefficients while P denotes the Legendre function.

$$\mathbf{B}_{INT}(r,\theta,\phi,t) = -\nabla\{a\sum_{n=1}^{N}\sum_{m=0}^{n}(\frac{a}{r})^{n+1}[\mathrm{g}_n^m(\mathrm{t})\cos\mathrm{m}\phi + \mathrm{h}_n^m(\mathrm{t})\sin\mathrm{m}\phi]\times P_n^m(\cos\theta)\} \quad (1)$$

Here, $\mathbf{B}$ is the magnetic field in the units of nT (nanoTesla). The major axis of the Earth accepted as 6378.137 km for the model. In the paper, the output magnetic field vector from the geomagnetic field model is shown as $\mathbf{B}_{\text{model}}$ and it is given in MAG coordinates. More information about coordinate systems may be found in [5], [6].

B. T89 (Tsyganenko) Model

Tsyganenko model (T89) is an empirical model based on large number of satellite data and gives a model of the magnetosphere. The model is freely available at NASA/GSFC, and at the website of the author [7]. In addition to the main field (internal) given by IGRF ($\mathbf{B}_{INT}$), it includes extraterrestrial effects ($\mathbf{B}_{EXT}$). More explicitly, $\mathbf{B}_{EXT}$ includes effects from magnetospheric ring current, tail current, magnetopause currents and Region 1 and 2 field aligned currents. Satellite data sets were categorised according to the geomagnetic activity index K_p and AE which represents the geomagnetic activity level and thus the strength of the external sources. The index is measured every 3-hours and change between 0-9 (seen in Table 1). The level of K_p is one of the inputs in the T89 model.

TABLE I. Intervals of the K_P Index

IOPT	1	2	3	4	5	6	7
K_p	0,0+	1-,1,1+	2-,2,2+	3-,3,3+	4-,4,4+	5-,5,5+	> =6-

C. CHAOS Model

CHAOS-6 is one of the very recently built model of the geomagnetic field based on more than 2 years of Swarm data and the latest ground observatory magnetic measurements, in addition to the data from previous satellite missions as Ørsted, CHAMP, SAC-C [8]. The model is freely available at DTU Space web-site [9]. Only the geomagnetically quietest data were used in this model, up to Kp <=2o for modelling the geomagnetic field. The CHAOS model was especially designed to be a good model of the quiet-time near-Earth geomagnetic field. The authors derived a new index, called RC, which describes the strength of the magnetospheric ring-current even during geomagnetic quiet conditions [10]. RC index is used to parameterize the external dipole (magnetospheric) field. In [11], the authors describe an approach that considers external and induced field parts based on the Dst (or Rc in this case) as they contribute differently at different satellite altitudes.

III. Analysis of Geomagnetic Models

In this study, a case study was considered to evaluate the geomagnetic field models by using a reliable magnetoemeter data on board a LEO satellite. For this purpose, CNOFS satellite was chosen from the list of Leo satellites on NASA/GSFC site. CNOFS magnetometer data were obtained from the NASA's public website CDAWeb. CNOFS (Communication / Navigation Outage Forecast System) is a US minisatellite launched on April 16, 2008 [12]. It has designed to forecast of the ionospheric irregularities in Earth's equatorial region. It has an elliptical, low inclination orbit at LEO. The information about CNOFS as altitude, magnetometer type, operational period, and the selected activity dates for the case study can be seen in Table 2. Two key dates that show high geomagnetic activity index, i.e. high AE, high Dst and Kp were selected. . Here AE index is the auroral substorm activity index.

TABLE II. Satellite Information (CNOFS).

CNOFS	
Altitude (km)	*390-736*
Magnetometer Type	*Fluxgate*
Operation Period	*April 16, 2008 to Nov 28, 2015*
Active Date	*April 05, 2010*
Quiet Date	*March 22, 2010*

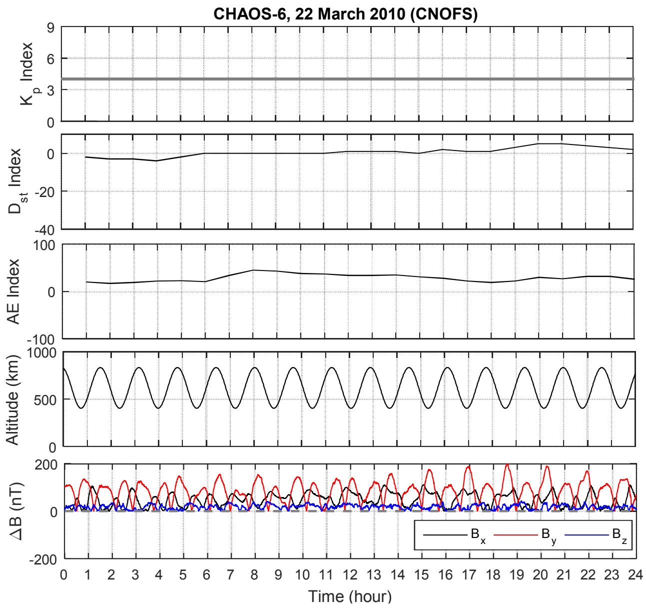

Fig. 1. Indices, altitude, and CHAOS-6 ΔB results for the quiet date (22 March 2010).

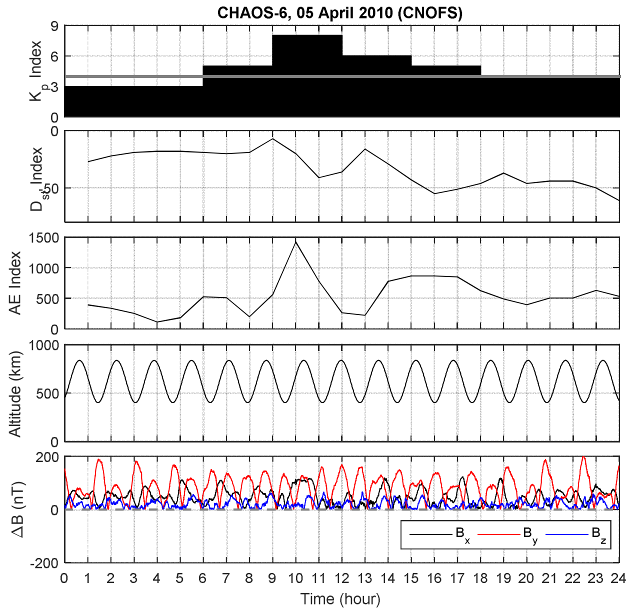

Fig. 2. From top to bottom: geomagnetic activity indices Kp, Dst, and AE, follwed by satellite altitude, and ΔB between CHAOS-6 and CNOFS during the geomagnetically active day (05 April 2010).

Figures 1 and 2 give Kp, Dst, AE, satellite altitude, and the difference between the magnetic field models predicted by CHAOS-6 model and observed by CNOFS from top to bottom respectively for the selected geomagnetically quiet (22 March 2010 in Figure 1) and active (5 April 2010 in Figure 1) days. In Figure 1 all three geomagnetic activity indices clearly indicate a day without any storm or substorm. In Figure 2, on the other hand, Dst varies around 50nT and shows a strong indication of the compressed magnetosphere while AE index rises up to 1000nT indicating the particle precipitation from the magnetosphere via substorms. Kp, the global magnetic activity index, shows a maximum of 8 corresponding to the maximum substorm activity time. These variations compared to their counterparts in Figure 1 indicate the presence of a geomagnetic storm and an auroral substorm in the geomagnetic tail.

The last panel in both panels gives the difference in the magnetic field components predicted by CHAOS model and observed by CNOFS and shown as ΔB . First thing that one can notice in Figure 1 is that there are considerable differences between the model predictions and the data even during the quiet day. Highest differences are seen in By component on the orders of 100nT while the least difference are found in Bz on the orders of 10s of nT. Secondly, the magnitude of the differences between the quiet day and active day is larger during the active day than quiet day. So the models actually predict closer to the data but this difference increases during the active day. This is especially clear in Bx and Bz components. We can see the geomagnetic storm affected the all three components of the magnetic fields. This is clearly seen in Bx, the north-south component of the geomagnetic field, and Bz, the vertical component, at the time of the substorm occurrence between 09:00 and 11:00 UT. Following the substorm a decrease in these components was recorded while By component shows an increase.

Root mean square errors for each magnetic field component are calculated for both active and quiet days and given in Table 3. Thus, Table 3 quantifies these differences between different models and compare them.

TABLE III. RMSE OF THE DIFFERENCES BETWEEN THE MODELS AND THE OBSERVATIONS FOR EACH MAGNETIC FIELD COMPONENT.

Activity Type	RMSE	IGRF-12	T89	CHAOS-6
Active	B_x (nT)	96.4190	55.482	56.380
	B_y (nT)	32.314	62.211	57.147
	B_z (nT)	112.25	23.652	24.920
Quiet	B_x (nT)	95.058	56.029	56.142
	B_y (nT)	24.114	59.471	56.333
	B_z (nT)	87.321	20.150	20.662

RMSE values in Table 3 indicate that both during the quiet day, T89 and CHAOS-6 give almost the same RMS error. T89 RMSE is slightlysmaller than those of CHAOS-6 except y-component of the field. This further indicates that T89 is slightly closer to the observed data by CNOFS. However, the differences between the model and observations are larger during the active day compared to those in quiet day for all models, including IGRF model. In fact, the differences are much larger in IGRF than those of T89 and CHAOS-6.

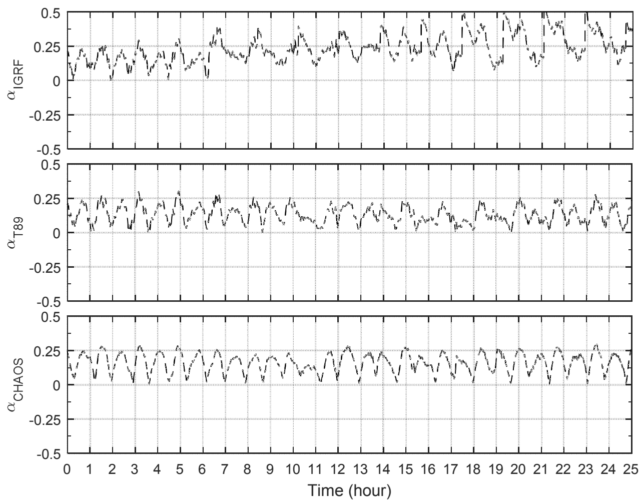

Fig. 3. The angle in degrees between the magnetic field vectors from magnetometer and the models (IGRF, T89, CHAOS-6) during the active day.

Although a magnetometer in a small satellite is a common sensor for attitude determination, both the magnetometer data and the magnetic field model are required to estimate the attitude angles. The difference in the components of the modelled and observed vectors is used as the unit vector; therefore the angle between them is of great importance in the attitude determination system. In Fig 3, the angle between the modeled and observed field vectors for IGRF, T89, and CHAOS-6 respectively is given for geomagnetically active day. We see that T89 and CHAOS-6 give almost stable variation throughout the interval with a maximum of about 0.25 degree. In IGRF model, however, there is slight trend that increases as time progresses. Also we can clearly see the effect of the magnetic storm from 09:00 to 11:00 UT as a decrease in the angle. Lower angles indicate that the magnetic fields during the substorm interval are indeed closer to the observations. That is, the magnetic activity cause a decrease in the magnetic components. However, the effects on the order of 0.25 degree for this case are not very significant on the satellite's attitude.

IV. Geomagnetic Model Use in Attitude Determination

Satellite's angular motion is determined by defining the dynamics and kinematics of the satellite. The difference between simulated and reference Euler angles can be found for each Magnetic Field Model representation. Therefore, the magnetometer measurements can be modelled as

$$\begin{bmatrix} B_x(\alpha,t) \\ B_y(\alpha,t) \\ B_z(\alpha,t) \end{bmatrix} = A \begin{bmatrix} B_1(t) \\ B_2(t) \\ B_3(t) \end{bmatrix} + \eta \tag{2}$$

where $\mathbf{B}_{\text{model}} = \begin{bmatrix} B_1(t) & B_2(t) & B_3(t) \end{bmatrix}^T$ is the Earth's magnetic field vector components in the orbital frame that were found using a geomagnetic field model, $B_x(t), B_y(t)$ and $B_z(t)$ represents the magnetometer measurements in the body frame as a function of time. Moreover, η is the zero-mean Gaussian white noise on the magnetometer measurements. In our case study, extended Kalman filter using only magnetometer measurements has been considered and the absolute errors on estimated attitude angles are presented in Table 4.

TABLE IV. Absolute Errors For Attitude using Kalman Filter

Activity Type	$\Delta\varphi$	IGRF-12	T89	CHAOS-6
Active	e_x (deg)	0.065	0.061	0.064
	e_y (deg)	0.114	0.073	0.075
	e_z (deg)	0.142	0.104	0.107
Quiet	e_x (deg)	0.064	0.061	0.064
	e_y (deg)	0.113	0.072	0.073
	e_z (deg)	0.141	0.103	0.106

In Table 4, $\Delta\varphi$ indicates the attitude estimation absolute error vector including the roll, pitch, yaw errors (e_x, e_y, e_z) respectively. Table shows the errors are so small and indicate that the attitude estimations are not affected significantly by the external magnetic fields for this case.

V. Conclusions

The main purpose of this study is to show how well the magnetic field components from geomagnetic field models represent satellite observations, especially at low Earth orbits. Satellite's attitude determination systems that use the magnetometer as attitude sensor are sensitive to the magnetic field models and magnetometer measurements, especially at LEO altitudes. The external magnetic field caused by the solar winds and interplanetary IMFs can modify the Earth's geomagnetic field. These can be predicted by using models such as T89 and CHAOS. Our preliminary comparisons presented in this study show that the proposed models work well against observations. However, if the satellite gets closer to the lower orbits, it can be said that the main geomagnetic field becomes dominant and the external effects decrease. Consequently it can be said that they do not show a significant impact on the LEO orbit satellite attitudes.

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References

[1] D. Cilden, Z. Kaymaz, and C. Hajiyev, "Extraterrestial magnetic field effects on attitude determination accuracy of small satellites," in *2015 7th International Conference on Recent Advances in Space Technologies (RAST)*, 2015, pp. 707–711.

[2] E. Thébault *et al.*, "International Geomagnetic Reference Field: the 12th generation," *Earth, Planets Sp.*, vol. 67, no. 1, p. 79, 2015.

[3] N. A. Tsyganenko, "A Magnetospheric Magnetic Field Model with a Warped Tail Current Sheet," *Planet. Sp. Sci.*, vol. 37, no. 1, p. 5, 1989.

[4] N. Olsen *et al.*, "CHAOS—a model of the Earth's magnetic field derived from CHAMP, Ørsted, and SAC-C magnetic satellite data," *Geophys. J. Int.*, vol. 166, no. 1, pp. 67–75, Jul. 2006.

[5] C. T. Russel, "Geophysical Coordinate Transformations," *Cosm. Electrodyn.*, vol. 2, pp. 184–196, 1971.

[6] D. Cilden, Z. Kaymaz, and C. Hajiyev, "Comparison of geomagnetic field from models and satellite observations for attitude determination purposes," in *2015 7th International Conference on Recent Advances in Space Technologies (RAST)*, 2015, pp. 483–487.

[7] N. A. Tsyganenko, "Modeling the Earth's Magnetosphere Using Spacecraft Magnetometer Data," 2008. [Online]. Available: http://geo.phys.spbu.ru/~tsyganenko/modeling.html.

[8] C. C. Finlay, N. Olsen, S. Kotsiaros, N. Gillet, and L. Tøffner-Clausen, "Recent geomagnetic secular variation from Swarm and ground observatories as estimated in the CHAOS-6 geomagnetic field model," *Earth, Planets Sp.*, vol. 68, no. 1, p. 112, 2016.

[9] C. C. Finlay, N. Olsen, S. Kotsiaros, N. Gillet, and L. Tøffner-Clausen, "The CHAOS-6 Geomagnetic Field Model," 2016. [Online]. Available: http://www.spacecenter.dk/files/magnetic-models/CHAOS-6/. [Accessed: 09-Mar-2017].

[10] N. Olsen *et al.*, "The CHAOS-4 geomagnetic field model," *Geophys. J. Int.*, vol. 197, no. 2, pp. 815–827, May 2014.

[11] N. Olsen, T. J. Sabaka, and F. Lowes, "New parameterization of external and induced fields in geomagnetic field modeling, and a candidate model for IGRF 2005," *Earth Planets Sp.*, vol. 57, pp. 1141–1149, 2005.

[12] G. D. Krebs, "C/NOFS (Communications / Navigation Outage Forecasting System)," 2016. [Online]. Available: http://space.skyrocket.de/doc_sdat/cnofs.htm. [Accessed: 11-Aug-2016].