

Finding Declinations Using Lookup Tables and Bilinear Interpolation in the Application of Digital Magnetic Compass

† Jeong-Bin Yim, Dae-Hee Kim*

† Division of Maritime Transportation System, Mokpo Maritime University, Mokpo 530-729, Republic Korea

* Graduate School of Mokpo Maritime University, Mokpo 530-729, Republic Korea

Abstract : This paper describes Declination interpolation method in the application of Digital Magnetic Compass(DMC) with small capacity memory for relatively low-priced system. The purpose of this study is to find accurate declination values using Declination Lookup Table(DLT) and Secular Variation Table(SVT) with the Bilinear interpolation method having four points data only. World Magnetic Model with Gauss coefficients produced by NOAA is used in the calculation of DLT and SVT at desired years. To verify the applicability of the proposed method, the simulation tests and the error analysis are carried out in this work. As results from tests, the interpolation error is within 0.01 degree that is much enough to implement high accurate DMC comparing with commercial DMCs on the market. In summary, the declination interpolation method, proposed in this study, can be useful in the application of DMC.

Key words : Digital Magnetic Compass, declination, interpolation, lookup table, World Magnetic Model

1. Introduction

Magnetic Compass does not point directly the true North and it is well known as Compass Error including Declination(or Variation) and Deviation in the field of navigation. The Declination causes the needle of Magnetic Compass to point more or less away from the true north. Even in the same location, Declination does not remain constant, but increases or decreases at a known annual rate. Thus, the Declination correction, except Deviation correction, is one of foremost concerns not only the Magnetic Compass but also the Digital Magnetic Compass (DMC) which is widely used in the modern navigation as one of substitute devices for the Gyrocompass(Ojeda and Borenstein, 2000; Yim and Sim, 2004; Yim, 2006; Saha, 2008; Hines, 2007; Honeywell, 2012).

In addition to the Declination correction, the ability to accurately and autonomously determine direction is fundamental for both navigation and pointing mobile devices. The advantage of Declination predictions by modern mathematical method with the power of microprocessor can create smart DMC which have capable of extremely accurate and reliable measurements of local magnetic field. The World Magnetic Model (WMM) is one of well known mathematical method to provide not only Declination for any desired location but also the complete geometry of magnetic fields.

The components of WMM consists of a degree and order 12 spherical-harmonic main field model comprised of 168 spherical-harmonic Gauss coefficients and a degree and 12 spherical-harmonic Secular Variation field model(Compston, 2012; DMA, 1993; Maus et al., 2010; NOAA, 2010).

In spite of the high accurate declination predictions by WMM, most of commercial DMC uses separate $\pm 180^\circ$ adjustments to collect Declination by manually. It is because of the location and the time dependency of WMM and the equation complexity of WMM, in particular.

The purpose of this study is to find declination values using simple lookup tables for Declinations and the Secular Variations with two-dimensional interpolation method rather than the complex equations and huge Gauss coefficients of WMM. In addition, the last goal of this work is to implement DMC with small capacity memory which can be store the simple lookup tables and can be relatively low-priced system. The coverage of target system is focused on the coastal waterways of Korea including the area of Latitude 32° to 40° North and Longitude 122° to 133° East.

2. Theoretical Background

2.1 Mathematical Model of WMM

The geomagnetic potential $V(r, \theta, \phi, \tau)$, described in the

† Corresponding author, jbyim@mmu.ac.kr 061)240-7170

* badajigi75mmu.ac.kr 061)240-7173

WMM(DMA, 1993; NOAA, 2010), expressed in terms of a spherical harmonic expansion of the following form:

$$V(r, \theta, \phi, \tau) = r_E \sum_{n=1}^N \left(\frac{r_E}{r} \right)^n \sum_{m=0}^n \{g_{n,m}(\tau) \cos m\phi + h_{n,m}(\tau) \sin m\phi\} P_n^m(\theta) \quad (1)$$

$$g_{n,m} = g_{n,m}(t_e) + \dot{g}_{n,m}(\tau - t_e) \quad (2)$$

$$h_{n,m} = h_{n,m}(t_e) + \dot{h}_{n,m}(\tau - t_e) \quad (3)$$

where:

r is radius from the center of Earth.

θ denotes the colatitude(90 degree - Latitude).

ϕ is Longitude.

r_E denotes the mean radius of Earth.

$g_{n,m}(\tau)$ and $h_{n,m}(\tau)$ are Gauss coefficients at time τ .

τ and t_e are the desired time in years and the base epoch of the model, respectively.

$P_n^m(\theta)$ denotes Legendre polynomial of degree n and order m .

$g_{n,m}(t_e)$ and $h_{n,m}(t_e)$ are Gauss coefficients of the WMM at the base epoch.

$\dot{g}_{n,m}(\tau - t_e)$ and $\dot{h}_{n,m}(\tau - t_e)$ are annual change rates of Gauss coefficients.

The Gauss coefficients and detailed information for the Eq.(1) are described in the "NOAA Technical Report: The US/UK World Magnetic Model for 2010-2015"(NOAA, 2010). Here, noting that the WMM is updated at five year intervals as like 2005 and 2010 etc. and is referred to by its epoch date such as WMM-2010 to the year of 2010. WMM-2010 is valid from 2010 to 2015.

2.2 Geomagnetic Components

The Earth's magnetic field $\mathbf{B}(r, \theta, \phi, \tau)$ in spherical coordinates is a vector quantity having three components such as $B_r(r, \theta, \phi, \tau)$, $B_\theta(r, \theta, \phi, \tau)$ and $B_\phi(r, \theta, \phi, \tau)$. The three components can be computed from the geomagnetic potential $V(r, \theta, \phi, \tau)$ as follows(DMA, 1993; Makovec, 2001; NOAA, 2010):

$$B_r(r, \theta, \phi, \tau) = -\frac{\partial V(r, \theta, \phi, \tau)}{\partial r} \quad (4)$$

$$B_\theta(r, \theta, \phi, \tau) = -\frac{1}{r} \frac{\partial V(r, \theta, \phi, \tau)}{\partial \theta} \quad (5)$$

$$B_\phi(r, \theta, \phi, \tau) = -\frac{1}{r \sin \theta} \frac{\partial V(r, \theta, \phi, \tau)}{\partial \phi} \quad (6)$$

where:

$B_r(r, \theta, \phi, \tau)$, $B_\theta(r, \theta, \phi, \tau)$ and $B_\phi(r, \theta, \phi, \tau)$ are the radial component measured outward positive, the co-elevation measured South positive and azimuthal component measured East positive, respectively.

2.3 Coordinate Transformation

The three geomagnetic components in Eqs.(1)~(3) are expressed as spherical coordinates. In the DMC application, meanwhile, the geodetic coordinates (λ, ϕ, h, τ) with latitude λ , longitude ϕ , and altitude h are often used and it uses WGS-84 ellipsoid as the reference ones. The three geomagnetic components can be computed to the rectangular components as follows(DMA, 1993; Makovec, 2001):

$$B_x(\lambda, \phi, h, \tau) = \cos \alpha B_\theta(r, \theta, \phi, \tau) - \sin \alpha B_r(r, \theta, \phi, \tau) \quad (7)$$

$$B_y(\lambda, \phi, h, \tau) = B_\phi(r, \theta, \phi, \tau) \quad (8)$$

$$B_z(\lambda, \phi, h, \tau) = \sin \alpha B_\theta(r, \theta, \phi, \tau) + \cos \alpha B_r(r, \theta, \phi, \tau) \quad (9)$$

where:

$$\alpha = \lambda - \frac{\pi}{2} + \theta$$

and, $B_x(\lambda, \phi, h, \tau)$, $B_y(\lambda, \phi, h, \tau)$ and $B_z(\lambda, \phi, h, \tau)$ are North-South magnetic component, East-West magnetic component and Vertical magnetic component, respectively.

From the three rectangular components in Eqs.(7)~(9), it is possible to construct following parameters:

$$B_H(\lambda, \phi, h, \tau) = \sqrt{B_x^2(\lambda, \phi, h, \tau) + B_y^2(\lambda, \phi, h, \tau)} \quad (10)$$

$$B_F(\lambda, \phi, h, \tau) = \sqrt{B_H^2(\lambda, \phi, h, \tau) + B_z^2(\lambda, \phi, h, \tau)} \quad (11)$$

$$D(\lambda, \phi, h, \tau) = \tan^{-1} \left(\frac{B_y(\lambda, \phi, h, \tau)}{B_x(\lambda, \phi, h, \tau)} \right) \quad (12)$$

where:

B_H , B_F and D are the horizontal intensity, the total intensity and Declination, respectively.

3. Declination Interpolations

3.1 Approaching Methods

Fig. 1 represents conceptual approaching procedures to find unknown declination $D_c(\phi, \lambda)$ at desired time t_c by two-dimensional(2-D) interpolation method. In this figure, t_1 , t_c and t_2 are the current year, the desired decimal year that is the current year in a decimal format to include any fraction of the year that has already passed and, the next

year of the current year, respectively. In addition, $D_{t_1}(\phi, \lambda)$ and $D_{t_2}(\phi, \lambda)$ are the interpolated Declinations at given time t_1 and t_2 , respectively.

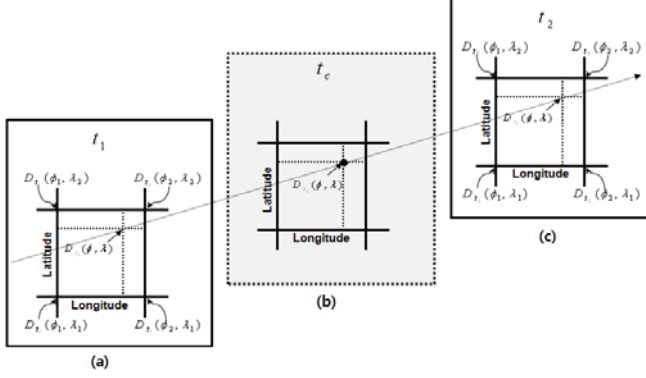


Fig. 1 Conceptual approaching procedures to find unknown declination $D_c(\phi, \lambda)$ at desired time t_c by two-dimensional interpolation method.

The determination procedures for the $D_c(\phi, \lambda)$ can be divided into five steps as follows:

Step 1: Prepare Declination Lookup Tables(DLT) using Eq.(12) for $D_{t_1}(\phi_n, \lambda_m)$ and $D_{t_2}(\phi_n, \lambda_m)$, where ϕ_n is longitude data set, $n = 1, 2, 3, \dots, N$ and N is total number of longitude data with the resolution of δ_ϕ . In addition, λ_m is latitude data set, $m = 1, 2, 3, \dots, M$ and M is total number of latitude data with the resolution of δ_λ .

Step 2: Find $D_{t_1}(\phi, \lambda)$ as shown in Fig. 1(a) by interpolation method with the four point declinations, $D_{t_1}(\phi_n, \lambda_m)$, $D_{t_1}(\phi_n, \lambda_{m+1})$, $D_{t_1}(\phi_{n+1}, \lambda_m)$ and $D_{t_1}(\phi_{n+1}, \lambda_{m+1})$ in the DLT of Step 1.

Step 3: Find $D_{t_2}(\phi, \lambda)$ as shown in Fig. 1(c) by interpolation method with the four point declinations, $D_{t_2}(\phi_n, \lambda_m)$, $D_{t_2}(\phi_n, \lambda_{m+1})$, $D_{t_2}(\phi_{n+1}, \lambda_m)$ and $D_{t_2}(\phi_{n+1}, \lambda_{m+1})$ in the DLT of Step 1.

Step 4: Find the annual change rate of declinations, called Secular Variation(SV), and it is differences between $D_{t_1}(\phi, \lambda)$ and $D_{t_2}(\phi, \lambda)$.

Step 5: Finally, determine $D_c(\phi, \lambda)$ using the interpolation theory as shown in the below.

The key idea of this interpolation procedure is to perform linear interpolation first in the declination $D_{t_1}(\phi, \lambda)$ and again in the declination $D_{t_2}(\phi, \lambda)$, then after find $D_c(\phi, \lambda)$.

3.2 Interpolation Theory

In mathematics, Bilinear interpolation is an extension of linear interpolation for interpolating functions of two variables on the rectangular grid as like shown in Fig. 1. In the other hand, Nearest neighbor interpolation and Bicubic interpolation are also well known as linear interpolation methods. The both of Bilinear and Bicubic produces smoother interpolation and smallest error than the Nearest methods. In addition, the mathematical algorithm of Bilinear is more simpler than the Bicubic and it is used only four points in the rectangular coordinates(Wikipedia, 2012; MATLAB, 2012).

In this study, thus, Bilinear interpolation method is used to determine $D_c(\phi, \lambda)$ at desired time t_c as shown in Fig. 1(b), and it can be expressed as follows:

$$D_c(\phi, \lambda) = D_{t_1}(\phi, \lambda) + [SV_{t_1, t_2}(\phi, \lambda) \tau_{t_1, t_c}] \quad (13)$$

where:

t_c , t_1 and t_2 represent the desired decimal year, the current year and the next year, respectively.

$D_{t_1}(\phi, \lambda)$ is the interpolated declination at time t_1 .

$SV_{t_1, t_2}(\phi, \lambda)$ denotes SV between $D_{t_1}(\phi, \lambda)$ and $D_{t_2}(\phi, \lambda)$.

τ_{t_1, t_c} is the time differences between time t_1 and time t_c .

$D_{t_1}(\phi, \lambda)$ and $D_{t_2}(\phi, \lambda)$ can be found using linear interpolation expansion of the following form:

$$D_{t_1}(\phi, \lambda) \approx [1-x(\phi) \ x(\phi)] \begin{bmatrix} D_{t_1}(x(\phi_n), y(\lambda_m)) & D_{t_1}(x(\phi_n), y(\lambda_{m+1})) \\ D_{t_1}(x(\phi_{n+1}), y(\lambda_m)) & D_{t_1}(x(\phi_{n+1}), y(\lambda_{m+1})) \end{bmatrix} \begin{bmatrix} 1-y(\lambda) \\ y(\lambda) \end{bmatrix} \quad (14)$$

$$D_{t_2}(\phi, \lambda) \approx [1-x(\phi) \ x(\phi)] \begin{bmatrix} D_{t_2}(x(\phi_n), y(\lambda_m)) & D_{t_2}(x(\phi_n), y(\lambda_{m+1})) \\ D_{t_2}(x(\phi_{n+1}), y(\lambda_m)) & D_{t_2}(x(\phi_{n+1}), y(\lambda_{m+1})) \end{bmatrix} \begin{bmatrix} 1-y(\lambda) \\ y(\lambda) \end{bmatrix} \quad (15)$$

where:

$x(\phi)$ and $y(\lambda)$ are corresponding values to ϕ and to λ , respectively. In addition, the two components laid on the rectangular coordinates in Fig. 1. Thus, the value of four points, needing in the interpolation, can be defined as $(x(\phi_n), y(\lambda_m)) = (0, 0)$, $(x(\phi_n), y(\lambda_{m+1})) = (0, 1)$, $(x(\phi_{n+1}), y(\lambda_m)) = (1, 1)$ and $(x(\phi_{n+1}), y(\lambda_{m+1})) = (1, 1)$.

3.3 Lookup Tables for Declination and Secular Variation

The software used in this work is MATLAB(2012). In addition, the MATLAB program `wrldmagn2.m` produced by The Math Works(2009) are used to construct Declination Lookup Table(DLT) for the base epoch year of 2011, 2012, 2013, 2014 and 2015.

Table 1 represents DLT for Declination $D_{t_1}(\phi_n, \lambda_m)$ in epoch time $t_1 = 2011.0$ that is base DLT during year of 2012 and it is one year passed after base epoch in WMM-2010. In addition, Fig. 2 shows contour plots for the DLT in Table 1 and is to explain the change pattern of Declinations along with the geographical positions in this areas. The conditions to construct DLTs are as follows:

- Limitation of geographical areas for DLTs: Longitude $122.0^\circ \text{ E} \sim 133.0^\circ \text{ E}$, Latitude $32.0^\circ \text{ N} \sim 40.0^\circ \text{ N}$
- Number of data and resolutions: $N=9$ and $\delta_\phi = 1.0^\circ$ for longitude, $M=12$ and $\delta_\lambda = 1.0^\circ$ for latitude.

The geographical area as mentioned in the conditions covers all of East, South and West sea of coastal waterways in Korea. This geographical limitation is to implement low-priced DMC having small memory capacity. In addition, the conditions for the resolution of $\delta_\phi = 1.0^\circ$ and $\delta_\lambda = 1.0^\circ$ is referenced the accuracy of WMM that is less than 1.0° .

Table 2 represents Secular Variation Table(SVT) for the epoch year 2011.0 that is differences between both of declinations in 2010.0 and in 2012.0. In addition, Fig. 3 shows contour plots for the SVT in Table 2 to explain the change pattern of the SV along with the geographical positions.

The seven contour plots from Fig. A-1 to Fig. A-7 in the Appendix represent the other DLTs and SVTs for the epoch year 2012.0, 2013.0, 2014.0 and 2015.0.

Table 1 DLT in epoch year 2011.0 (Unit: degree)

m	n	ϕ_n											
		λ_m	122	123	124	125	126	127	128	129	130	131	132
1	32	5.71	5.85	5.98	6.10	6.19	6.28	6.34	6.39	6.42	6.44	6.43	6.41
2	33	5.97	6.12	6.26	6.38	6.48	6.57	6.64	6.70	6.74	6.75	6.75	6.73
3	34	6.24	6.39	6.54	6.66	6.78	6.87	6.95	7.01	7.05	7.07	7.08	7.06
4	35	6.50	6.67	6.82	6.95	7.07	7.17	7.25	7.32	7.36	7.39	7.40	7.39
5	36	6.77	6.94	7.10	7.24	7.37	7.47	7.56	7.63	7.68	7.71	7.72	7.71
6	37	7.04	7.22	7.39	7.53	7.66	7.77	7.87	7.94	7.99	8.03	8.04	8.04
7	38	7.32	7.50	7.67	7.82	7.96	8.08	8.17	8.25	8.31	8.35	8.37	8.37
8	39	7.59	7.78	7.96	8.12	8.26	8.38	8.48	8.56	8.63	8.67	8.69	8.69
9	40	7.87	8.07	8.25	8.41	8.56	8.68	8.79	8.88	8.94	8.99	9.01	9.02

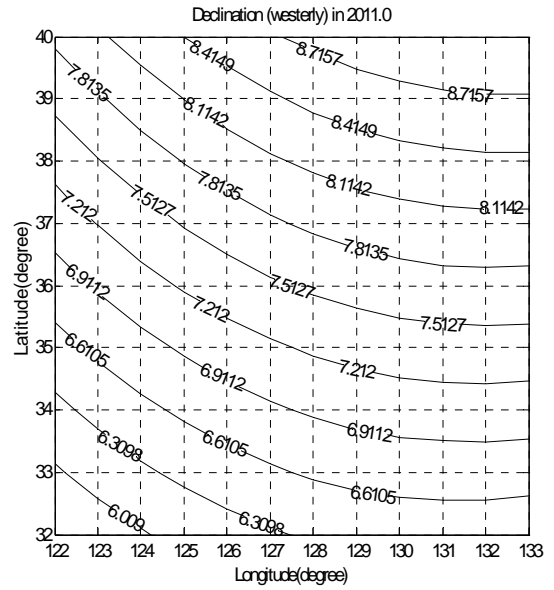


Fig. 2 Contour plot for the DLT in epoch year 2011.0

Table 2 SVT in epoch year 2011.0 (Unit: degree $\times 10^{-2}$)

m	n	ϕ_n											
		λ_m	1	2	3	4	5	6	7	8	9	10	11
1	32	4.41	4.26	4.11	3.96	3.81	3.66	3.51	3.37	3.23	3.09	2.97	2.85
2	33	4.34	4.24	4.08	3.92	3.77	3.61	3.45	3.30	3.16	3.01	2.88	2.75
3	34	4.38	4.22	4.05	3.89	3.72	3.56	3.39	3.23	3.08	2.93	2.79	2.66
4	35	4.37	4.20	4.02	3.85	3.67	3.50	3.33	3.16	3.00	2.84	2.69	2.55
5	36	4.35	4.17	3.99	3.81	3.63	3.44	3.26	3.09	2.92	2.75	2.59	2.44
6	37	4.33	4.15	3.96	3.77	3.57	3.38	3.19	3.01	2.83	2.66	2.49	2.33
7	38	4.31	4.12	3.92	3.72	3.52	3.32	3.12	2.93	2.74	2.55	2.38	2.21
8	39	4.29	4.08	3.88	3.67	3.46	3.25	3.04	2.84	2.64	2.45	2.26	2.09
9	40	4.26	4.05	3.83	3.61	3.39	3.18	2.96	2.75	2.54	2.34	2.14	1.95

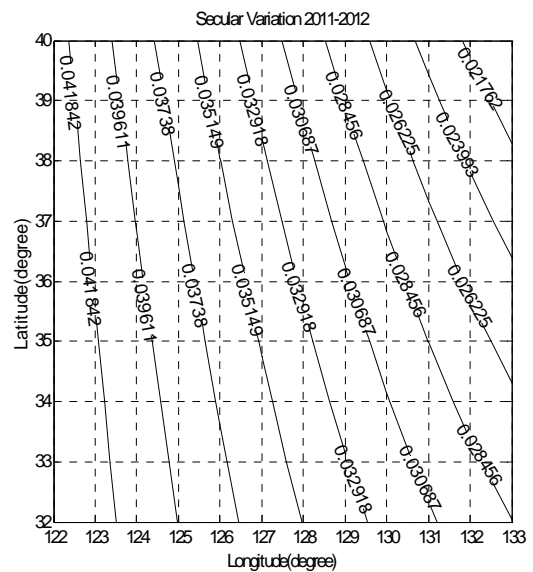


Fig. 3 Contour plot for the SVT in epoch year 2011

3.4 Simulation Tests and Evaluation Results

To verify the applicability of proposed interpolation method using DLT and SVT, simulation tests with the location data in Table 3 and the decimal year data in Table 4 are carried out. In addition to the simulation tests, the analysis of the error by Declination interpolation is also discussed in this work.

The RMS(Root Mean Square) errors $e(L_i, Y_j)$ of interpolated declinations are calculated as

$$e(L_i, Y_j) = \sqrt{[D_{t_c}^{WMM}(\phi, \lambda) - \tilde{D}_{t_c}(\phi, \lambda)]^2} \quad (16)$$

where:

L_i is location data set, $i=1,2,3,\dots,I$ and I is total number of data.

Y_j represents desired year data set, $j=1,2,3,\dots,J$ and J is total number of data.

$D_{t_c}^{WMM}(\phi, \lambda)$ is declinations with Gaussian coefficients of WMM.

$\tilde{D}_{t_c}(\phi, \lambda)$ represents interpolated declinations by proposed method.

Table 5 represents the calculation results for the RMS errors $e(L_i, Y_j)$ with 8-by-6 test parameters in Table 3 and in Table 4. In table 5, all of $e(L_i, Y_j)$ for the 8-by-6 test parameters are within 0.01 degree and, the ranges of mean error varies from 1.440×10^{-3} (minimum) to 3.505×10^{-3} (maximum).

Here, noting that the accuracy of Digital Magnetic Compass varies from 0.5 degree in maximum to 1.0 degree in minimum in case of the commercial DMCs(Ojeda et al., 2000; Hines, 2007; Honeywell, 2012).

Thus, it is clearly known that the amounts of declination interpolation errors of within 0.01 degree are much enough to have high accurate Digital Magnetic Compass.

Table 3 The data set of locations for interpolation tests

L_i			
i	Location Name	Latitude λ (North)	Longitude ϕ (East)
1	Incheon	37° 28 ' 00.1 "	126° 36 ' 49.2 "
2	Gunsan	35° 58 ' 04.8 "	126° 37 ' 10.2 "
3	Mokpo	34° 48 ' 13.2 "	126° 24 ' 16.5 "
4	Kwangyang	34° 53 ' 29.6 "	127° 39 ' 22.8 "
5	Busan	35° 03 ' 45.4 "	129° 06 ' 35.8 "
6	Pohang	36° 01 ' 56.8 "	129° 22 ' 54.7 "

Table 4 The data set of desired years for interpolation tests

Y_j		
j	Desired Year	Decimal Year t_c
1	January 1, 2011	2011.00000
2	July 1, 2011	2011.49589
3	January 1, 2012	2012.00000
4	July 1, 2012	2012.49727
5	January 1, 2013	2013.00000
6	July 1, 2013	2013.49589
7	January 1, 2014	2014.00000
8	July 1, 2014	2014.49589

Table 5 Calculation results for the RMS errors

Error $e(L_i, Y_j)$ (Unit: degree $\times 10^{-3}$)									mean (Unit: degree $\times 10^{-3}$)	s.t.d. (Unit: degree $\times 10^{-6}$)
$i \backslash j$	1	2	3	4	5	6	7	8		
1	1.474	1.468	1.471	1.465	1.469	1.463	1.466	1.460	1.467	4.384
2	1.442	1.438	1.443	1.438	1.443	1.438	1.443	1.438	1.440	2.485
3	3.524	3.515	3.514	3.505	3.505	3.495	3.495	3.485	3.505	12.93
4	2.139	2.136	2.142	2.139	2.145	2.142	2.148	2.145	2.142	3.968
5	1.697	1.691	1.693	1.688	1.690	1.684	1.687	1.681	1.689	4.960
6	3.094	3.085	3.083	3.074	3.072	3.063	3.061	3.052	3.073	13.861

4. Conclusions

The Declination interpolation method using lookup tables for Declinations and Secular Variations with Bilinear interpolation are discussed and proposed in this paper. The proposed method is to find declination values with simple lookup table for the Declinations and Secular Variations rather than the complex equations and huge Gauss coefficients of WMM.

The applicability of the proposed method to the application of Digital Magnetic Compass has been verified through the simulation tests and error evaluations. The RMS error due to interpolations shows within 0.01 degree that is much enough to have high accurate Digital Magnetic Compass.

In summary, the declination interpolation method, proposed in this study, can be useful method in the application of Digital Magnetic Compass.

References

- [1] Compston Drew(2012), *International Geomagnetic Reference Field (IGRF) Model*, MATLAB Central. (URL <http://www.mathworks.com/matlabcentral/fileexchange/34388-international-geomagnetic-reference-field-igrf-model>, access dated: December 5, 2012).
- [2] DMA(1993), *Military Specification: World Magnetic*

Model(WMM), Defence Mapping Agency MIL-W-89500, pp. 1-22.

[3] Hines Lindsey(2007), *Digital Compass Accuracy*, white paper, pp. 1-15. (URL <http://www.mbari.org/education/internship/07interns/papers/InternPapers/LHines.pdf>. access dated: December 5, 2012).

[4] Honeywell(2012), *Magnetic Sensors: Compassing Solutions*, (URL <http://www.magneticsensors.com/compassing-solutions.php>, access dated: December 5, 2012).

[5] MATLAB(2012), *Programming, MATLAB Version 7.6 (R2008a)*. (URL <http://www.mathworks.co.kr>).

[6] Makovec L. Kristin(2001), *A Nonlinear Magnetic Controller for Three-Axis Stability of Nanosatellites*, Master Thesis in Aerospace Eng., Virginia Polytechnic Institute and State University, pp. 20-26.

[7] Maus S., Manoj C., Rauberg J., Michaelis I., and Luhr H.(2010), "NOAA/NGDC candidate models for the 11th generation International Geomagnetic Reference Field and the concurrent release of the 6th generation Pomme magnetic model," *Earth Planets Space*, Vol 62, pp. 729-735.

[8] NOAA(2010), *Technical Report: The US/UK World Magnetic Model for 2010-2015*, pp. 1-46. (URL <http://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml>, access dated: December 5, 2012)

[9] Ojeda Lauro and Borenstein Johann(2000), "Experimental Results with the KVH C-100 Fluxgate Compass in Mobile Robots, Proc. of the AISTED International Conference, Robotics and Applications 2000, pp. 1-7.

[10] Saha Ram Padha(2008), *A Study on the Prediction of Earth's Variation Using World Magnetic Model*, Master Thesis, Mokpo Maritime University, pp. 1-37.

[11] The Math Works(2009), *Matlab Program: wrldmagm2.m*, Revision: 1.1.6.4, Date:2009/08/14. (URL http://www.control.aau.dk/uav/reports/12gr1052/matlab_svn/my_functions/WMM/wrldmagm2.m, access dated: December 5, 2012).

[12] Wikipedia(2012), *Tutorial for Bilinear interpolation*, (URL http://en.wikipedia.org/wiki/Bilinear_interpolation, access dated: December 5, 2012).

[13] Yim Jeong-Bin and Sim Yeong-Ho(2004), "A New Method for the Acquisition of Deviation Coefficients B and C at a Single Magnetic Heading," *Journal of Korean Institute of Navigation and Port Research*, Vol. 28, No. 10, pp. 851-859.

[14] Yim Jeong-Bin(2006), "Development of Ship's Digital Compass Using Flux-gate Sensors with High Accuracy," *Journal of Korean Institute of Navigation and Port Research*, Vol. 30, No. 5, pp. 321-329.

Appendix

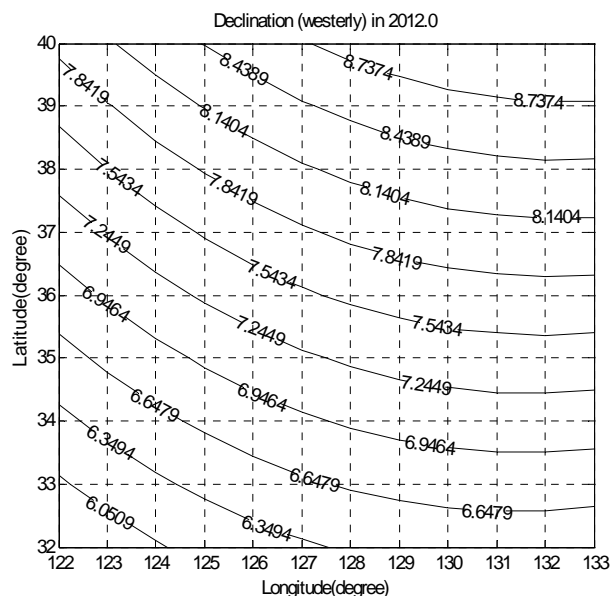


Fig. A-1 Contour plot for Declination in epoch year 2012.0

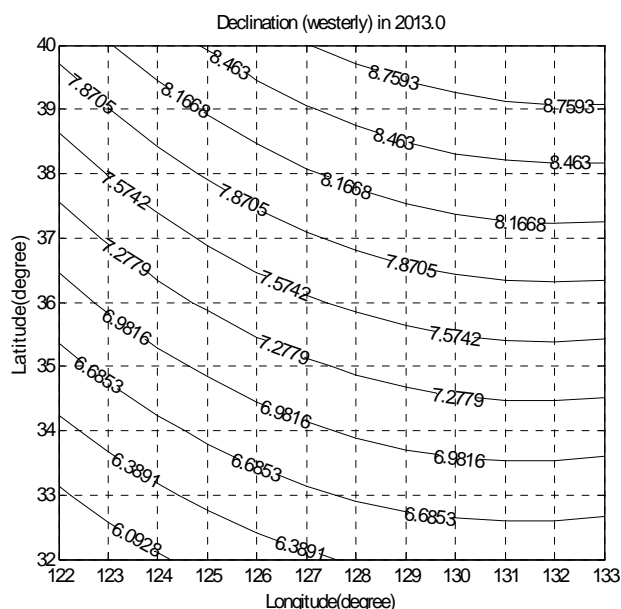


Fig. A-2 Contour plot for Declination in epoch year 2013.0

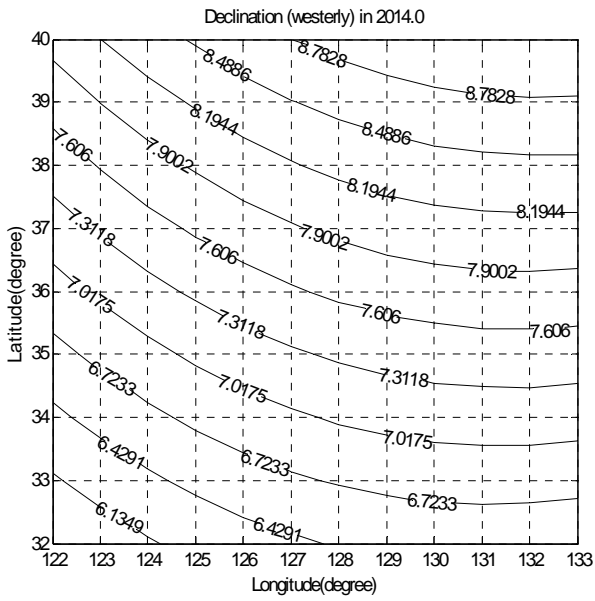


Fig. A-3 Contour plot for Declination in epoch year 2014.0

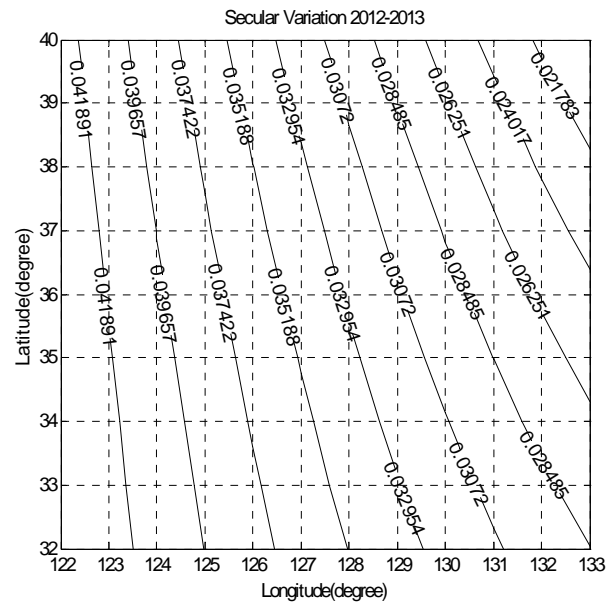


Fig. A-5 Contour plot for SV in epoch year 2012.0

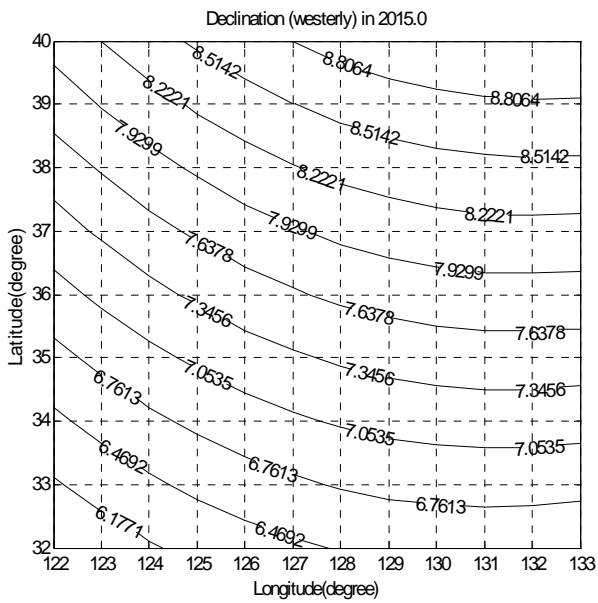


Fig. A-4 Contour plot for Declination in epoch year 2015.0

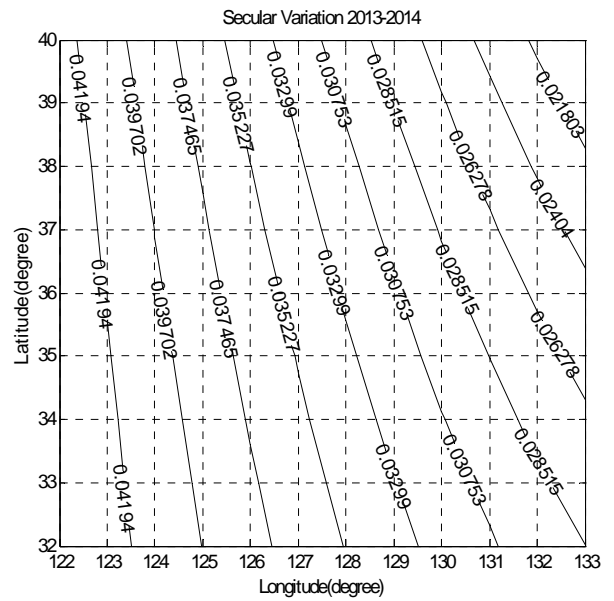


Fig. A-6 Contour plot for SV in epoch year 2013.0

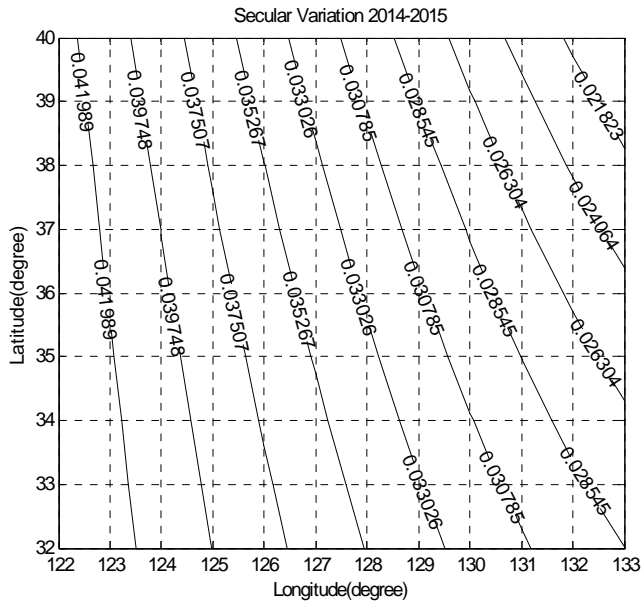


Fig. A-7 Contour plot for SV in epoch year 2014.0

Received 10 December 2012
Revised 24 December 2012
Accepted 26 December 2012