How Accurate Geomagnetic Regional Modeling Using Ordinary Kriging For Clustered Distributed Data?: New Insight From Indonesian Archipelago

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Express Letter

Keywords: Geomagnetic, Geostatistics, Modeling, Regional, and Repeat Station.

Posted Date: August 30th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-773577/v1

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How accurate geomagnetic regional modeling using ordinary kriging for clustered distributed data?: new insight from Indonesian Archipelago

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Abstract

Indonesia relies only on the limited number of repeat station networks due to the archipelago setting with the extensive sea with the clustery distributed pattern. This paper explored geostatistical modeling to overcome that typical data characteristic. The modeling used repeat station data from the 1985 to 2015 epoch. The research used ordinary kriging (OK) compared to the Spherical Cap Harmonic Analysis (SCHA) and Polynomial. The results show that the root means square error (RMSE) of each declination, inclination, and total intensity vary among epochs. OK method for declination component produces smaller average RMSE (7.67 minutes) than SCHA (9.26 minutes) and Polynomial (7.97 minutes). For the inclination component, OK has an average RMSE of 9.55 minutes, smaller than SCHA (10.05) but slightly higher than Polynomial (9.36 minutes). For the total intensity component, OK produce an average RMSE of 63.58 nT, smaller than SCHA (82.24 nT) and Polynomial (68.97 nT). The finding shows that the kriging method can be a promising method to model the regional geomagnetic field, especially in the area of limited available data and clustered distributed data.

Keywords

Geomagnetic, Geostatistics, Modeling, Regional, and Repeat Station.
1. Introduction

The value and position of the geomagnetic field are dynamic. This is caused by its fluid and material motion (Elsasser, 1956; Brandenburg, 2007). Therefore, some observation and modeling are needed to produce a geomagnetic field map periodically. Geomagnetic field mapping began in 1957 at the International Union of Geodesy and Geophysics (IUGG) meeting in Toronto. The meeting became the birth of the World Magnetic Survey (Heppner, 1963). In 1960, a mathematical model of spherical harmonic analysis was recommended and the model became the basis for the International Geomagnetic Reference Field/IGRF (Zmuda, 1969; Macmillan and Finlay, 2011). The IGRF is an international agreement generated from the spherical harmonic model of the geomagnetic field and its secular variations (Mandea and Macmillan, 2000).

The IGRF model is updated every five years under the auspices of the International Association of Geomagnetism and Aeronomy (IAGA). Improvement to the IGRF’s accuracy continues to increase by adding the truncation order of the spherical harmonic analysis equation incorporated by satellite data. However, it still has limitations in terms of accuracy and spatial resolution (Maus et al., 2005). Furthermore, the spherical harmonic analysis equation cannot be used for a geomagnetic field in the form of an orthogonal area (Mandea and Purucker, 2005). This has led to the introduction of new regional geomagnetic field models in the hope to produce a more accurate model.

Based on the IAGA resolution No. 23 (1963): “Repeat station measurements during the International Years of the Quiet Sun (IQSY) in support of the World Magnetic Survey (WMS)”. The Badan Meteorologi, Klimatologi dan Geofisika (BMKG), or the Meteorological, Climatological, and Geophysical Agency of Indonesia has conducted measurements in repeat stations to cover the Indonesia region starting from 1985. These
measurements were then routinely carried out every five years. The locations of the Indonesia repeat stations comply with some special terms determined professionally by the IAGA (Newitt et al., 1996). Moreover, the nature of Indonesia as an archipelago causes the clustered distribution of the repeat stations. The cluster distribution is shown by the nearest neighbor analysis with negative value (Z score = -0.78). Repeat station distribution is difficult to make uniformly. The repeat station locations cannot be placed on the water, the site can't be accessed. No locations were found that met the standards for repeat stations (Newitt et al., 1996). This concern gives more difficult challenges to the regional geomagnetic field modeling framework in Indonesia (Fig. 1).

In general, the methods used in regional geomagnetic field modeling are the polynomial modeling method (Alldredge, 1981; Düzgit et al., 1997), the spline and the Taylor expansion (Hall and Meyer, 1976; Wahba, 1990), spherical cap harmonic analysis (Haines, 1985), revised spherical cap harmonic analysis (Thébault et al., 2004), and revised spherical cap harmonic analysis for the Earth’s surface (Thébault, 2008). The existing method generally needs dense data for modeling. The boundary effect of the existing method is also affected by the data configuration. Numerical instability due to wide data gaps resulting from sparse data patterns needs to be balanced with statistical or physical regulation to increase model reliability (Torta, 2020).

To propose a new regional geomagnetic field modeling with limited and clustered data patterns, the geostatistical method can be an alternative method. Geostatistical methods are very accurate in modeling natural resources (Goovaerts, 1997), such as underground river flows (Huysmans and Dassargues, 2009) and reservoirs of oil and gas (Poon et al., 1993; Xi and Morgan, 2019). Geostatistical methods were developed to predict the distribution of the percentage of ores in mining (Krige, 1951). A geostatistical method is also defined as a
method to predict the value of the data property, which is not covered by the sample data
distribution or sparse data pattern (Webster and Oliver, 2008).

Geostatistical methods are classified into two types: traditional algorithms and geostatistical
algorithms (Isaaks and Srivastava, 1989). The weighted values in the traditional algorithm
bases on a geometrical distance of the surrounding estimator data. This includes the Inverse
Distance Weighting (IDW), Nearest Neighbor or Polygon, and the Triangulation methods.
The geostatistical algorithm, on the other hand, uses the structure or statistics of distances
from the surrounding estimator data to weigh the data property. One of the geostatistical
algorithms is Kriging. Kriging considers the distance and direction of the array of sample
data points to reflect spatial correlations. Kriging can produce good estimates for anisotropic
data and clustered distribution (Goovaerts, 1997; Arfaoui and Inoubli, 2013). There are
several kinds of Kriging algorithms: e.g., Simple Kriging, Ordinary Kriging (Wackernagel,
1995; Montero et al., 2015), Universal Kriging, Kriging with External Drift or KED (Hengl
al., 2003), and the Collocated Cokriging or CC (Rivoirard, 2001).

However, the geostatistical method has never been used for regional geomagnetic field
modeling. Searching on the Scopus indexed papers using the keywords "geomagnetic” and
“regional,” which obtained 3,524 papers. Among the obtained papers, there are only a few
which contain the 'geostatistic' keyword (Fig. 2). There are only two papers that contain the
'geostatistic' word. One paper is discussing the history of regression and model-fitting in
Earth science (Howarth, 2001), and the second paper discusses the estimation of regional
covariance of Total Electron Content (Ghoddousi-fard, 2019). Neither of the papers
discusses modeling the regional geomagnetic field. Accordingly, the purpose of this paper
is to explore the accuracy of the geostatistical method in regional geomagnetic field
modeling and mapping.
2. Data and Method

We used repeat station data from the BMKG in the epoch 1985 to 2015. The BMKG has conducted measurements in repeat stations to cover the Indonesia region starting from 1985. The location for most of the repeat stations is located at the airport. It has the advantage that apart from fulfilling the special requirements for the location of the repetition station, it can also support the calibration of runway azimuth, which is important for aircraft navigation (Rasson and Delipetrov, 2006; Loubser and Newitt, 2009). These measurements were then routinely carried out every five years. The data has been reduced by diurnal variation and secular variation to get the same unit of time in each epoch.

To validate the regional geomagnetic model resulted from the geostatistical methods and the existing methods (SCHA and Polynomial methods), we use 15% of the total number of the existing repeat station data gathered from 1985 to 2015. The data used for the model validation purpose is excluded from the modeling process. The composition and the distribution of the validation data are selected randomly (Fig. 1). For the main geomagnetic field, we use the Definitive Geomagnetic Reference Field (DGRF) data generated from IGRF-13. The reason for using such data is that the global model is more accurate than the regional one (Talarn et al., 2017).

This research tested the accuracy of the geostatistical method and the existing modeling methods to model the regional geomagnetic field inside Indonesia. The SCHA method is selected as the sampling method from the mathematical method group (SCHA, R-SCHA, and R-SCHA2D). SCHA is chosen because it has been used often by researchers in recent decades (Torta, 2020). The potential field equation V in the SCHA is the following:

\[ V(r, \theta, \lambda) = a \sum_{k=0}^{K} \sum_{m=0}^{M} \left( \frac{a}{r} \right)^{n_k (m+1)} \left( g^{i, m}_{n_k} \cos(m \lambda) + h^{i, m}_{n_k} \sin(m \lambda) \right) \Phi^{n_m}_{n_k} \theta \]
\[ V = \text{geomagnetic potency}, a = \text{Earth’s radius} \ (6,371.2 \ \text{km}), r = \text{radial distance of the set location from the Earth’s core}, \theta = \text{Colatitude} \ (90^\circ - \text{latitude}), \lambda = \text{longitude}, P_{n^k}^m = \text{Legendre function of the associated Schmidt non-integer } n_k(m) \ \text{and } m, g_{n_k}^{l,m} \ \text{and } h_{n_k}^{l,m} = \text{are the Gaussian Earth’s core magnetic field coefficient, } g_{n_k}^{l,m} \ \text{and } h_{n_k}^{l,m} = \text{are the Gaussian lithosphere magnetic field coefficient.}

The Polynomial method is selected as the sample for the interpolation method group because it is more accurate than the SCHA, as is evident in the regional geomagnetic modeling conducted in China (Gu et al., 2006) and corresponding to geomagnetic field sign (Geese et al., 2011). The Taylor polynomial normal field model equation is given below (Mandea and Purucker, 2005; Gu et al., 2006; Geese et al., 2011):

\[ C(\theta, \phi) = \sum_{n=0}^{N} \sum_{m=0}^{m} A_{nm} (\theta - \theta_0)^{n} (\phi - \phi_0)^{m}. \]  

\[ \hat{Z}(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i). \]  

\[ Z_{OK}(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i). \]
This method is known to produce good estimation results in the Earth science field (Cățeanu and Ciubotaru, 2020; Massimi et al., 2020; Nistor et al., 2020; Sunkari et al., 2020).

The data from the repeat stations are cut by the diurnal variation using the station data in the BMKG observatories. The data are then checked and refined using the secular variation and brought to a certain epoch. This needs to be done because the measurement processes in some repeat stations were not conducted at the same time as others. After the data are uniform in epoch (for example, epoch 2015.0), then each component X, Y, and Z are decremented with the DGRF data, producing the geomagnetic field anomaly. Mathematically, we write those steps in formulas (4), (5), and (6).

\[
\Delta X = X - \text{DGRF}_X \quad (4)
\]

\[
\Delta Y = Y - \text{DGRF}_Y \quad (5)
\]

\[
\Delta Z = Z - \text{DGRF}_Z \quad (6)
\]

\(\Delta X\), \(\Delta Y\), and \(\Delta Z\) are the geomagnetic field anomaly for each component, \(\text{DGRF}_X\), \(\text{DGRF}_Y\), and \(\text{DGRF}_Z\) are the main geomagnetic definitive data obtained from the IGRF-13 model for each component.

The geomagnetic anomaly data from the repeat stations (exclude the 15% validation locations) are used to estimate the geomagnetic values of the validation locations. The number of sample data and locations used for the calculation (for each epoch) is shown in Table 1. Equation (3) is used for the OK method, equation (1) is used for the SCHA method, and equation (2) is used for the polynomial method with \(\theta_0 = 2^\circ\) and \(\phi_0 = 117.5^\circ\). We then analyze the resulted estimation data to determine the mean root square error (MRSE) level. Therefore, we can investigate the accuracy of the geostatistical method in modeling the regional geomagnetic field compared with the existing method.
3. Results

Using the sample data as shown in Table 1 (i.e., in the epoch 1985 to 2015), the OK, SCHA, and polynomial methods are applied to each of the geomagnetic components, such as declination, inclination, and total intensity, to estimate the validation location. The OK method uses two variogram functions: i.e., stable and exponential. The selection of the variogram affects the estimation results of the Kriging method (Webster and Oliver, 2008).

For the SCHA method, the truncated $8^{th}$ order for the geomagnetic anomaly is used because the root mean square error (RMSE) values in the $\Delta X$, $\Delta Y$, and $\Delta Z$ components for the $k^{th}$ order, with $k \geq 8$, is smaller and stable. For the polynomial method, the $5^{th}$ order is used because it produces a small RMSE value.

The accuracy of declination value information is very important, especially for the lower declination area in Indonesia: i.e., -2 to 4.5 degrees. These data also support the directional drilling with a value of 0.1 degrees (Macmillan, 2004). The root mean square error (RMSE) of the Declination Component is varied in each epoch. The least average value of 7.67 minutes is given by the OK method using the stable variogram (Fig. 3a). The OK method, using the exponential variogram, produces the RMSE value with an average difference of only 0.01 minutes higher (i.e., relatively the same) than the stable variogram. However, the SCHA and the polynomial methods produce higher average RMSE values of 1.59 and 0.29 minutes, respectively.

The smallest average RMSE value of 6.68 minutes of the inclination component is obtained using the OK method with the stable variogram (Fig. 3b). The OK method, using the exponential variogram and the polynomial methods, produces slightly smaller differences of 0.13 and 0.19 minutes, respectively. These differences are smaller than the difference observed in the Declination Component. The inclination value range used in the sample test
is between -5 to -38 degrees. However, the highest average RMSE value of 0.74 minutes is also produced by the SCHA method. The RMSE value fluctuation of the Total Intensity Component is the same as that of the Inclination Component (Fig. 3c). This value confirms the contours of the two in the sample data, which has some value degradation along the latitude. The smallest average RMSE value of 63.58 nT is obtained by the OK method using the stable variogram. This value is smaller than the one obtained by the SCHA and the polynomial methods: i.e., 18.67 nT and 5.39 nT, respectively.

4. Discussion

The results show that the geostatistical method produces a good estimation or model in the regional geomagnetic field with clustered distribution patterns such as Indonesia. The geostatistics using OK result in 1.5 minutes more accurate than SCHA and polynomial for the declination component geomagnetic field. The OK also results in 18.67 nT more accurate than SCHA and the polynomial for the total intensity component. But for the inclination component, OK is less accurate than polynomial (0.19 minutes higher). However OK is still more accurate than SCHA (0.5 minutes lower).

The difference of the RMSE values in the Declination, Inclination, and the Total Intensity Components are affected by the spatial distribution pattern of the repeat stations. The existing methods (SCHA and the polynomial) require regular and more closely spaced data to produce accurate models (Torta, 2020; Bonito et al., 2021). The OK method can fit various types of data distributions such as random, clustered, and anisotropic (Webster and Oliver, 2008; Zhao et al., 2014). Ordinary kriging applies differently weight between clustered with the different number of data set. Therefore It can reduce bias in the estimation (Isaaks and
Srivastava, 1989). Meanwhile, SCHA and polynomial don’t consider the different number of data set between clusters.

The average RMSE in the inclination component of OK is slightly higher than the polynomial method (0.19 minutes). However, in the declination and total intensity components whose contours are curving isoline, the OK method produces a smaller average RMSE than polynomials. OK can fit the curving isoline of geomagnetic components. Gu et al. (2006) found that SCHA and polynomial result in bigger RMSE in curving isoline. The Declination’s contours in Indonesia deviate along the longitude and have more curving isoline (Fig. 4). The Total Intensity and Inclination Component’s contours have more constant value along the latitude, forming a straight line. The polynomial method is more accurate in straight geomagnetic isoline (Ryan, 1997).

The result also shows that the number of repeat stations affects the RMSE, as suggested by the previous study (Korte and Thébault, 2007; Barraclough and De Santis, 2011; Korte and Lesur, 2012). This effect can be shown by comparing RMSE between epoch 2015 (with 28% additional sample data) and the average of RMSE epoch 1990 to 2010 (Fig. 3d). The accuracy of OK increase by 47% for the total intensity component. This increase of accuracy of OK is 18% higher than SCHA and polynomial. The accuracy of OK also increases by 19% for the inclination component, which is 9% higher than SCHA and polynomial. For the declination component, the accuracy of OK also increases by 50%, 9% higher than SCHA. But a bit lower (3%) than polynomial. This result showed that OK gets increased accuracy and realistic representation of the geomagnetic field by the addition of data sample same as in SCHA (Torta, 2020) and polynomial (Kotzé and Korte, 2016).

Furthermore, the chosen variogram doesn’t give much different results in OK modeling. The difference between stable variogram and exponential is only 0.01 minutes for the Declination Component, 0.3 minutes for the Inclination Component, and 0.19 nT for the Total Intensity.
Component. Generally, the variogram has intrinsic characteristics that affect to estimate of data in each direction (Webster and Oliver, 2008). Variogram has 3 parameters such as nugget, range, and sill (Armstrong, 1998). Nugget is a constant value for all distances greater than zero caused by intrinsic randomness of regionalized variables and the sampling process (Carrasco, 2010). Range is the maximum distance value for which there is still a correlation between data (Webster and Oliver, 2008). Sill is limiting the value of variogram that no longer correlation between data (Carrasco, 2010). However, OK produces small variogram-type effects. It is likely caused by the sum of unknown mean weights $(\mu) = 1$ (Matheron, 1963; Wackernagel, 1995; Montero et al., 2015) and the clustered distribution of sample data produce identical variogram parameters (Mälicke et al., 2018).

5. Concluding Remarks

The OK method gives a good result in modeling the regional geomagnetic field. This research gives the geostatistical method a chance to play its new role in modeling the regional geomagnetic field in the area of limited and clustered distribution pattern data. However, for the research to explore the other geostatistical methods (for example IDW, KED, CC, and Cokriging) is needed to know which method works best.

List of abbreviations

BMKG The Badan Meteorologi, Klimatologi dan Geofisika, or the Meteorological, Climatological, and Geophysical Agency of Indonesia;

CC Collocated Cokriging;

DGRF The Definitive Geomagnetic Reference Field;

IAGA The International Association of Geomagnetism and Aeronomy;
Availability of data and materials

The geomagnetic data for epochs 1985 to 2015 used in this study was extracted from BMKG. The Definitive Geomagnetic Reference Field (DGRF) data generated from IGRF-13 ([https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html](https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html)). The analysis software tool using Matlab with License ID: 1106171. Nearest neighbor analysis to determine the type of data sample distribution was calculated using Z score ([http://ceadserv1.nku.edu/longa//geomed/ppa/doc/NNA/NNA.htm](http://ceadserv1.nku.edu/longa//geomed/ppa/doc/NNA/NNA.htm)). The geomagnetic regional model epoch 2015 is available at [http://doi.org/10.5281/zenodo.5094914](http://doi.org/10.5281/zenodo.5094914)

Competing interest
We declare that we have no significant competing financial, professional or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

**Funding**

This research was supported and funded by BMKG and the Indonesian Higher Education Directorate through the PDD schema with contact number: 2246/UN1/DITLIT/DIT-LIT/PT/2021

**Authors’ contributions**

M.S. performed the analysis of geomagnetic regional model using SCHA, Taylor polynomial and OK, E.H. performed the research framework, and S.A. performed contributed to the preparation of the manuscript.

**Acknowledgments**

We thank the Meteorological, Climatological, and Geophysical Agency of Indonesia (BMKG) for supporting and granting access to repeat stations data used in this research. We also thank the Indonesian Higher Education Directorate through the PDD schema for supporting the research funding.
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Table 1. Number of Sample and Validation Data Used in Each Epoch from the Epoch 1985 to 2015

| Epoch | Total Repeat Stations | Number of Sample Locations (Repeat Stations) | Number of Validation Locations (15% from the total repeat stations) |
|-------|-----------------------|---------------------------------------------|---------------------------------------------------------------|
| 1985  | 59                    | 50                                          | 9                                                             |
| 1990  | 53                    | 45                                          | 8                                                             |
| 1995  | 53                    | 45                                          | 8                                                             |
| 2000  | 53                    | 45                                          | 8                                                             |
| 2005  | 54                    | 46                                          | 8                                                             |
| 2010  | 53                    | 45                                          | 8                                                             |
| 2015  | 68                    | 58                                          | 10                                                            |
FIGURES

Figure 1. Distribution of the 45 sample locations and 8 locations for the data validation, Epoch 2010. Z score is nearest neighborhood analysis value. Negative score indicates cluster distribution. The data validation was selected randomly from each epoch, 15% as of the total number of repeat stations.
Figure 2. The occurrences of words (the titles, keywords, and abstracts) from the 3,524 Scopus-indexed papers using the keywords “geomagnetic” and “regional”. The geostatistic keyword has only two occurrences.
Figure 3. Root mean square error (RMSE) from the OK method with Stable Variogram, OK with Exponential Variogram, SCHA, and polynomial method between data estimation and validation data for epoch 1985 to 2015 in each geomagnetic component. (a) Declination Component (minutes); (b) Inclination Component (minutes); (c) Total Intensity (nT); (d) RMSE decreased in percent due to the addition of 28% sample data.
Figure 4. Geomagnetic chart for epoch 2015.0 in Indonesia, (a) Declination Comp. with Δ=0.5°, (b) Inclination Comp. with Δ=5°, and (c) Total Intensity Comp. with Δ=1000 nT.
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