GEOMAGNETIC SURVEYS BY THE GEOSPATIAL INFORMATION AUTHORITY OF JAPAN AND THE CONTRIBUTION OF THE KAKIOKA MAGNETIC OBSERVATORY

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ABSTRACT

The Geospatial Information Authority of Japan (GSI) has been conducting geomagnetic surveys in Japan since 1949 to clarify the geographical distribution of direction, intensity of the geomagnetic field, and their secular variations. Recently, we have carried out continuous observations at geodetic observatories and continuous geomagnetic stations and repetitive observations at several first-order geomagnetic stations. The results of the surveys, "geomagnetic charts", have been published every 10 years. In 2011, GSI released the newest geomagnetic charts for the epoch 2010.0 created by adopting a new spatial-temporal model. This model needs continuous data of good quality. In addition to the GSI geodetic observatories, the Kakioka Magnetic Observatory, which has been conducting high-quality and stable observations for 100 years, makes a large contribution.

Keywords: Geomagnetic charts, Spatial-temporal model, Kakioka Magnetic Observatory

1   INTRODUCTION

The Geospatial Information Authority of Japan (GSI) is the administrative organization that conducts mapping in Japan. For example, GSI provides various base maps, notably the topographical map series of 1/25000 that covers the whole country. These maps include declination information because there are some differences between the true north used in these maps and the magnetic north indicated by a magnetic compass. Nowadays, the frequency of magnetic compass use is decreasing with the development of satellite positioning with GNSS and digitalization of seamless maps. However, declination information is without doubt established in people's daily lives. For example, small magnetic sensors are installed in smart phones. Thus presently, declination is still essential information for connecting geospatial information to the magnetic compass. Because the geomagnetic field changes every moment, continuous observations are required.

GSI conducts geomagnetic surveys to reveal the geomagnetic distribution around Japan. In 1939, the Land Survey Department of the Imperial Japanese Army (the predecessor of GSI) started carrying out geomagnetic surveys. At the same time, GSI conducted geomagnetic observations at the Kakioka Magnetic Observatory of the Japan Meteorological Agency (JMA) for magnetometer calibration. Since the end of WW II, GSI has been conducting nationwide geomagnetic surveys. GSI created the set of "geomagnetic charts" that began gathering the results of geomagnetic surveys in 1970, and it has been updating them every 10 years. In 2011, GSI released the newest geomagnetic charts for the epoch 2010.0 (Ueda et al., 2012). The new "spatial-temporal model" is applied to create these charts. This new model needs long-term, continuous, high-quality data. Hence the Kakioka Magnetic Observatory's data play an important role. This paper will introduce GSI's geomagnetic surveying along with Kakioka's contribution to GSI's surveying.

2   GEOMAGNETIC OBSERVATION

GSI has facilities for geomagnetic observation - 3 geodetic observatories and 11 continuous geomagnetic stations. In addition, GSI has about 100 first-order geomagnetic stations and about 850 second-order geomagnetic stations. Figure 1 shows the location of these facilities and geomagnetic stations. The geodetic observatories and the continuous geomagnetic stations have automatic geomagnetic instruments. Meanwhile, first- and second-order geomagnetic stations have no instruments for continuous observation; there are only buried granite stones in the ground to perform repetitive observations at the same point. We call the repetitive observations performed with these stones "first- or second-order geomagnetic surveys".
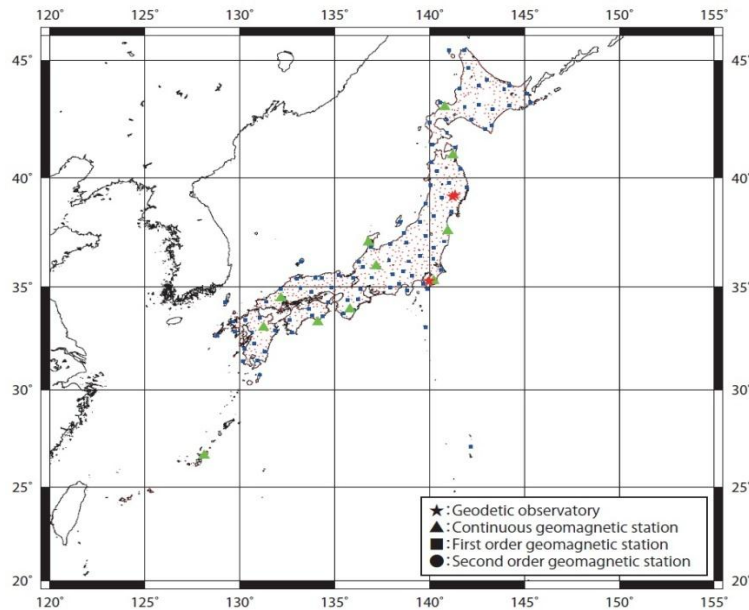
Figure 1. Location map of GSI's geomagnetic facilities and stations

2.1 First- and second- order geomagnetic stations

The geomagnetic field changes both spatially and temporally. In order to clarify the spatial distribution of the geomagnetic field and its secular variations in Japan, GSI has been carrying out nationwide geomagnetic surveys at the first-order geomagnetic stations since 1949. In the beginning of the first-order geomagnetic surveys, a magnetometer was set up at a first-order geomagnetic station and performed as many as 17 observations of declination and inclination a day. After a measurement, the average of the 17 results was compared with hourly data from Kakioka Magnetic Observatory as reference data, and the daily average value was estimated. Recently, we set fluxgate magnetometers underground and proton magnetometers on the ground to measure some geomagnetic components. In addition, we performed 3 observations of declination and inclination a day. Then, we can get the absolute daily data by combining variation data from fluxgate magnetometers with absolute values obtained from proton magnetometers and results of our measurements. These survey results are compiled and published as a "Report of Geomagnetic Survey (ISSN 2185-9159)". Until 2008 these reports were printed in booklet form. Currently, they may only be viewed on the website.

The second-order geomagnetic surveys are simpler than the early first-order geomagnetic surveys. They are conducted only four times per hour to measure the declination, inclination, and total force. Owing to the small number of measurements, they are able to be performed at many stations. The first nationwide second-order geomagnetic surveys were carried out from 1952 to 1957 at about 800 stations. After that, the second nationwide second-order geomagnetic surveys were carried out from 1958 to 1968. They have not been performed since then.

2.2 Geodetic observatories

Geodetic observatories are observation facilities that regularly perform continuous geomagnetic observation. GSI has three geodetic observatories in Japan. Nowadays, all facilities are unmanned.

GSI has built facilities one after another for general regular observations at Kanozan since 1956, and the GSI staff has conducted geomagnetic and astronomical surveying regularly. Based on these facilities, the geodetic observatory was established in 1962, and some staff worked there. However, an electrification plan for the Uchibo-railways 7 km away from the observatory appeared around 1965. Because direct current emitted from the railway might cause geomagnetic disturbance, it was necessary that the continuous geomagnetic observation be moved to another appropriate place. Nevertheless, geomagnetic observation at Kanozan was worth continuing from the viewpoint of the effective use of long-period data (several minutes or longer) and the role of monitoring crustal activities. Therefore, the new Mizusawa Geodetic Observatory was established in the northeast part of Japan in 1969. Thus, the geodetic observatory at Kanozan was renamed the Kanozan Geodetic Observatory.

In 1971, the route of the Tohoku superexpress, which passes near the Mizusawa Geodetic Observatory, was determined. Since short period geomagnetic pulsation due to passing trains may influence natural current, the Esashi Observatory was built in 1980 as an unmanned observatory operated by the Mizusawa Geodetic Observatory. GSI has been conducting regular continuous observation at the Esashi Observatory.

In these three observatories, GSI conducts total magnetic force observation using an Overhauser magnetometer (GSM-11, GSM-19) and a Proton magnetometer (PMS-7010) and makes variance observations of declination, inclination, and the horizontal component using a three-axis Fluxgate magnetometer (MB-162) every second. Absolute observation is performed once a month at each observatory to determine the baseline. The data provided by geodetic observatories are shown in Table 1.

Table 1. Information produced from geodetic observatories

Data category	Detail	WDC	GSI HP
Minutely data in IAGA format (*.min)	Definitive minutely data	O	O
Hourly data in IAGA format (*.hor)	Definitive hourly data	O	O
Hourly data (*.hor)	Definitive hourly data in tabular format		O
Monthly Graph (*.gif)	Geomagnetic variation graph		O

All the geomagnetic observation data can be found on the GSI website. In addition, GSI provides IAGA-format data to the World Data Center (WDC) for Geomagnetism, Kyoto. We also provide 1-second data on request. In the future, 1-second data will be provided on the GSI website.

2.3   Continuous geomagnetic stations

In 1996, continuous geomagnetic stations (see Figure 2) were installed at 11 locations all over Japan. These stations aim to raise the precision of the geomagnetic survey and to play the role of reference-like observatories in local areas. These stations give two advantages to Japanese geomagnetic surveying: first, because the space density of the continuous observation points increases, the information about geomagnetism all over Japan becomes more accurate. Next, when we perform first-order geomagnetic surveys near continuous geomagnetic stations, we can use the continuous observation data from those stations instead of instruments installed temporarily. When we install a magnetometer during a first-order geomagnetic survey, it is necessary to wait until its measuring data are stabilized. However, if we can use the continuous geomagnetic station's data, the operation becomes simpler and shorter.
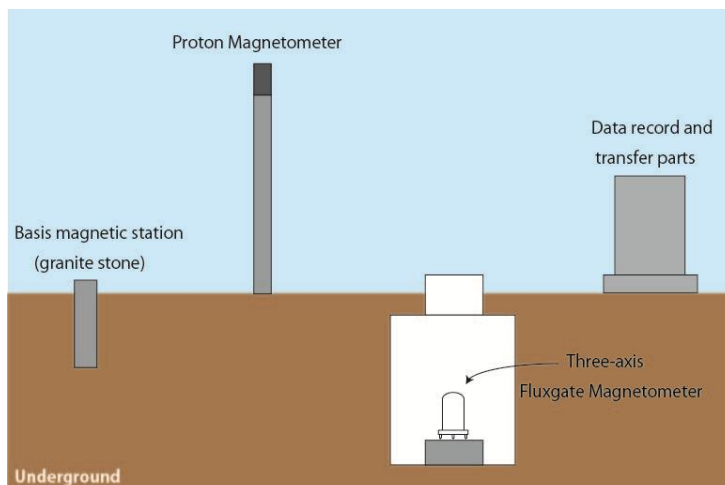

Figure 2. Configuration of continuous geomagnetic stations

The continuous geomagnetic stations play an intermediary role between geodetic observatories and first-order geomagnetic stations and have granite stones called basis magnetic stations and geomagnetic observation instruments. A proton magnetometer (PMS-700) installed about 2 meters above the ground and a three-axis

Fluxgate magnetometer (FGE-91) installed underground measure the total force and the geomagnetic component's variation every minute, respectively. The data are transmitted to GSI through the public phone lines. To calculate the definitive data, the absolute observation is carried out once a year at the base magnetic stations that are stone monuments laid in the ground. GSI provides these data as shown in Table 2.

Table 2. Information produced from continuous geomagnetic stations

Data category	Detail	GSI HP
Minutely data (*.obs)	Raw data at each devise	O
Minutely data in IAGA format (*.min)	Definitive or Provisional minutely data	O
Hourly data in IAGA format (*.hor)	Definitive or Provisional hourly data	O
Monthly graph (*.gif)	Geomagnetic variation graph	O

Although these absolute observations are performed under conditions favorable for magnetic measurement, collected data can have lower accuracy than that at the observatories because of poor baseline control and short-term noise. Therefore, the data at continuous geomagnetic stations are provided only on the GSI website. Because data continuity is important, we provide the raw data from each station. Because the absolute observations are performed once a year, these data are provided as provisional data. After an absolute observation, we remake the provisional data to become the definitive data.

3   GEOMAGNETIC CHARTS

GSI compiles the results of geomagnetic surveys in geomagnetic charts, which represent the distribution of geomagnetic components (declination (D), inclination (I), total force (F), horizontal component (H), and vertical component (Z)) and are updated every 10 years with the oldest being from 1970. The geomagnetic charts for the epoch 1970.0 (see Figure 3) reflect the results of the first- and second-order geomagnetic surveys (second-order geomagnetic surveys ended in 1968) and represent the spatial magnetic anomalies accurately (GSI, 1973). In 2011, GSI released the newest geomagnetic charts for the epoch 2010.0.
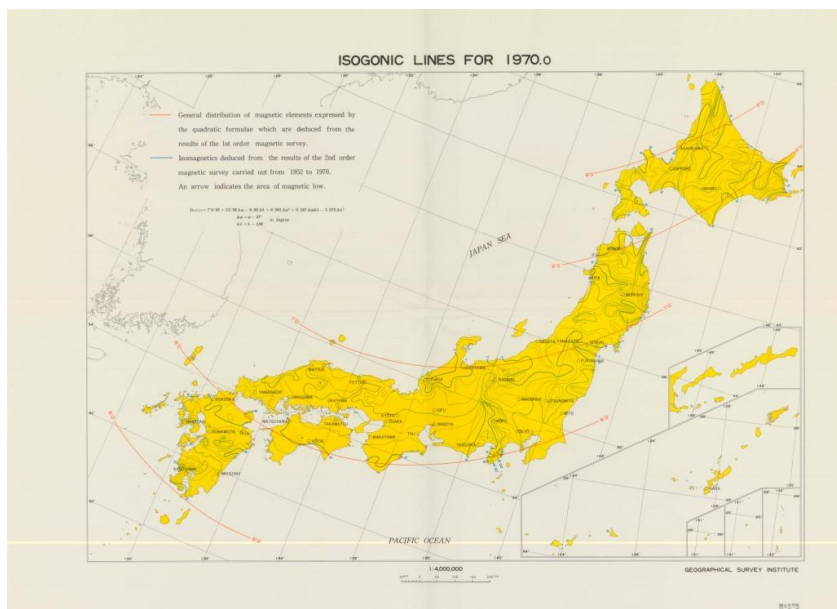

Figure 3. Geomagnetic chart for the epoch 1970.0 (declination)

3.1   Geomagnetic Charts for the epoch 1970.0 to 2000.0

Geomagnetic charts up to the epoch 2000.0 were created by adding estimated variations from the results of the first-order geomagnetic surveys to the previous geomagnetic charts. This method of variational estimation was

described in Shirai et al. (2002). In this section, we briefly show the procedure of this method. To estimate the variation for a decade, we use the results of repetitive first-order geomagnetic surveys performed all over Japan.

First, we approximate the time series of the repetitive first-order geomagnetic survey results with a quadratic expression,

$$H(t) = \alpha t^2 + \beta t + \gamma, \tag{1}$$

where t is the date of the observation and H is the observed geomagnetic value. Three coefficients, α, β, and γ, are estimated by the least-squares method using sets of dates and results from the first-order geomagnetic surveys. We get the geomagnetic value at the previous and latest epoch from Eq. 1. By subtracting the previous values from the latest values, we can get the variation for a decade at i-th station (ΔH_i). We apply this procedure to geomagnetic stations with enough observed data.

Next, we spatially approximate the variations at i-th station using a quadratic polynomial function,

$$\Delta H_i = S + A\Delta\phi_i + B\Delta\lambda_i + C(\Delta\phi_i)^2 + D\Delta\phi_i\Delta\lambda_i + E(\Delta\lambda_i)^2, \tag{2}$$

where $\Delta\phi$ and $\Delta\lambda$ are $\phi - 37°$ and $\lambda - 138°$, respectively. The coefficients (S, A, B, C, D, and E) are estimated by the least-squares method using sets of variations for a decade and location of the geomagnetic stations. After that, we calculate the variation for a decade at every first- and second-geomagnetic station. Finally, the calculated values are added to the previous geomagnetic charts. This method was used to make the geomagnetic charts up to the epoch 2000.0.

3.2   Spatial-temporal model

The model described above needs many results from first-order geomagnetic stations in terms of space and time to improve the quality of the geomagnetic charts. However, the number of staff engaged in a geomagnetic survey has been decreasing. Moreover, the magnetic stations where we can conduct stabilized observations have also been decreasing due to changes in the surrounding environment. Therefore, a new modeling method that can keep the quality with limited data is required. GSI developed new geomagnetic models (for example, Ji et al., 2006b; Ji et al., 2007) after release of the geomagnetic charts for the epoch 2000.0. Consequently, GSI created a new geomagnetic model in 2010, the "spatial-temporal model".

3.2.1   Details of the spatial-temporal model

In this model, the Natural Orthogonal Components (NOC) and quadratic polynomial function methods were chosen to construct a model based on the observed data. Because the geomagnetic field changes both spatially and temporally, the time series of a field component (H_i) at an arbitrary geographical position (ϕ, λ) is represented as

$$H_i(\phi, \lambda) = \sum_k T_k X_{ik}(\phi, \lambda), \tag{3}$$

where k is the number of certain combinations of the temporal function (T_k) and the spatial function (X_{ik}). Because the geomagnetic field observed in Japan shows similar temporal variations, we can obtain the common temporal function by using the NOC method. It allows us to compute the spatial function at an arbitrary position. In this model, the quadratic polynomial function was chosen to compute the spatial function. The new spatial-temporal model was made through the following steps.

In the first step, common temporal functions are obtained by the NOC method. Because this model was based on the geomagnetic charts for the epoch 1970.0 and used yearly geomagnetic values, we chose the data from five GSI (KNZ and MIZ) and JMA (MMB, KAK, and KNY) geomagnetic observatories. We did not include the data from 11 continuous geomagnetic stations because of the shortage of observation time. As a result, the sum of several orders of multiplication of spatial functions and temporal functions are obtained. In particular, the first four components (T_k, k=1-4) are adopted because the higher orders of T_k are nearly zero.

In the second step, the yearly values at the first-order geomagnetic stations are estimated. Although the first-order geomagnetic stations do not have yearly values, we have already obtained the yearly temporal function (T_k) from the first step. Therefore, we can estimate the most appropriate spatial function (X_{ik}) by using the least-squares method.

Finally, we combine both functions using Eq. 3 and get the yearly geomagnetic variations at the first-order geomagnetic stations. Ji et al. (2006a) concluded that the precision of the yearly value estimation by the NOC method depended on the time of observations at the first-order geomagnetic stations. We tried some patterns of the set of first-order geomagnetic stations categorized by observed years. As a result, we selected 27 first-order geomagnetic stations that have been observed since 2004.

As a third step, the spatial functions are represented by approximated location functions. We perform the NOC method once again using the yearly data estimated in former steps from 5 geomagnetic observatories and 27 first-order geomagnetic stations. As a result, a common temporal function and 32 spatially dispersed spatial functions are obtained. After that, we estimate the approximate quadratic polynomial function of normalized latitude ($\Delta\phi = \phi - 37°$) and longitude ($\Delta\lambda = \lambda - 138°$),

$$X_{ik} = S_k + A_k \Delta\phi_i + B_k \Delta\lambda_i + C_k \left(\Delta\phi_i\right)^2 + D_k \Delta\phi_i \Delta\lambda_i + E_i \left(\Delta\lambda_i\right)^2 . \tag{4}$$

We estimate coefficients by using the least-square method.

As a final step, geomagnetic values at all geomagnetic stations are obtained. As we have already obtained the coefficients in Eq. 4 and know the position of all first- and second-order geomagnetic stations, we can calculate the spatial function at arbitrary geomagnetic stations. After that, we estimate the geomagnetic model value at an arbitrary station by combining the temporal function with the calculated spatial function. With estimated models at all geomagnetic stations, we can create the geomagnetic charts for an arbitrary epoch, which is an important advantage of this model over the past GSI model, which was updated every 10 years. We can also get secular variations visibly if we combine every year's geomagnetic charts. When we update the next geomagnetic charts using the new spatial-temporal model in the future, we will go through the same steps. If the newest values of geomagnetic field value (H_i) are used as the input values, temporal function (T_k) and spatial function (X_{ik}) can be updated. These new functions can be different from the ones in the past. This means that the model values of the geomagnetic field change depending on the number of temporal data. For example, the calculated model values at the epoch 2010.0 using 2010.0 models (using data up to 2010) are different from those values calculated using 2015.0 models. However the difference between them will not be so large but should be far smaller than the contour interval of the geomagnetic charts (ten minutes in D and I, 100 nT in F, H, and Z). Therefore, GSI does not update past geomagnetic charts.

3.2.2   Accuracy of the spatial-temporal model

To estimate the accuracy of the new spatial-temporal model, we first compare the geomagnetic charts for the epoch 2000.0 created by the old model with those created by the new spatial-temporal model. Figure 4 shows the difference between the geomagnetic values for the epoch 2000.0 created by the new and old models.
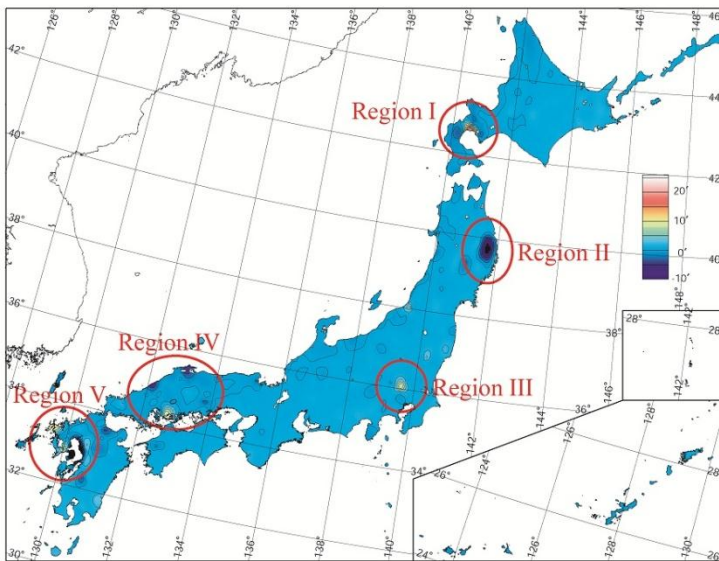

Figure 4. Difference between geomagnetic charts for the epoch 2000.0 created by the two models (declination)

Although there are some singularities around Region I to V, they have some obvious causes. First, the original geomagnetic charts for the epoch 2000.0 were created removing irregular values, which caused the singularities around Regions I, II, III, and IV. Second, the result of the recent first-order geomagnetic survey has some gaps from the results of the past surveys, which cause the singularity around Region V. While we doubted the accuracy of the geomagnetic survey, we could not identify the cause of this gap. Therefore, we decided to use the observed values. In the other area, there are very small differences. As an accuracy estimation index, we calculated root-mean-square error (RMSE) of the difference between the two models indicated in Table 3.

Table 3. RSME of the differences between the two models

D (minute)	I (minute)	H (nT)	Z (nT)	F (nT)
2.57	2.59	30.8	32.4	38.6

For D and I, the RSMEs are less than 3 minutes. For H, Z, and F, the RMSEs are less than 40 nT. Both of the RSME values are less than the contour interval of declination. Therefore, it is clear that the new model can reproduce the old model.

Next, we calculate the difference of the spatial-temporal model between model values and the results of the first-order geomagnetic surveys because only first-order geomagnetic surveys have been performed since 1970. The RMSE differences are given in Table 4.

Table 4. RMSE of the differences between the model calculation and the input data

D (minute)	I (minute)	H (nT)	Z (nT)	F (nT)
1.59	1.26	15.7	13.4	11.2

For D and I, the RMSEs are less than 2 minutes. For H, Z, and F, the RMSEs are less than 20 nT. While the geomagnetic charts contain some errors, they are less than the contour intervals.

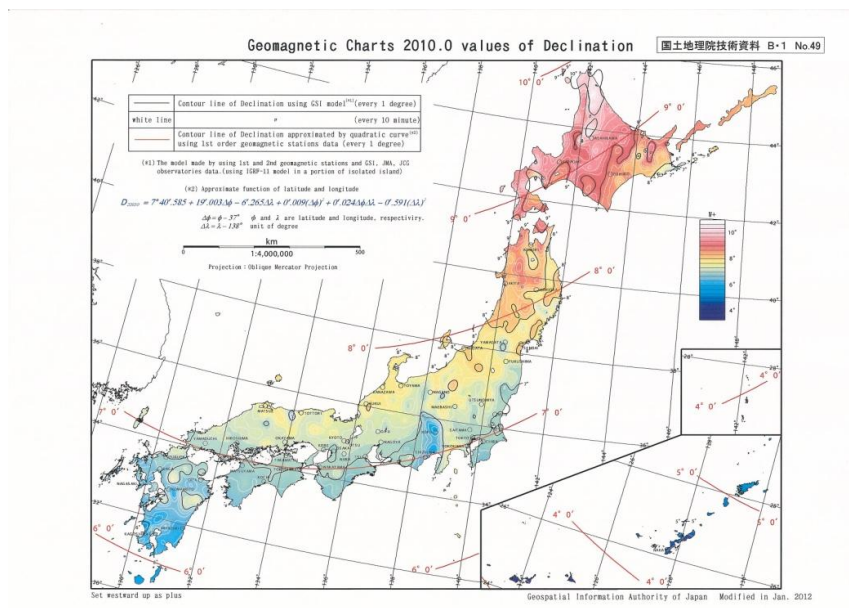## 3.3   Geomagnetic Charts for the epoch 2010.0

Figure 5. Geomagnetic charts for the epoch 2010.0 (declination)

In 2011, GSI released the newest geomagnetic charts for the epoch 2010.0 (see Figure 5), using the spatial-temporal

model. Plotted data are obtained from model values at first- and second-order geomagnetic stations, annual mean values of observation results at 3 GSI geodetic observatories and 3 JMA magnetic observatories, and annual mean values of observation results at 11 continuous geomagnetic stations.

4   CONCLUDING REMARKS

In this paper, we introduce GSI's geomagnetic survey. GSI has been conducting nationwide movable geomagnetic surveying since WW II. The results of these surveys are data of unprecedented value. In addition, GSI operates 3 geodetic observatories and 11 continuous geomagnetic stations. This observation data is released on the GSI website.

Furthermore, GSI has released geomagnetic charts as a result of these surveys and observations. The magnetic charts are maps of the geomagnetic distribution in Japan. GSI has updated them every 10 years since 1970. In 2011, GSI released the newest geomagnetic charts for the epoch 2010.0 using a new spatial-temporal model. To use this model, long-term, continuous, stable and high quality data is required. Although GSI has 3 geodetic observatories, just 2 observatories' data can be used from the view of long term data. Kakioka's data is suitable for this model's basic data because the Kakioka Magnetic Observatory has been conducting high-quality and stable observations for 100 years. Therefore, Kakioka's continuous data plays a very important role.

5   REFERENCES

Geographical Survey Institute (1973) Magnetic Charts for the Epoch 1970.0. *Bulletin GSI* 19(1), pp 131-137.

GSI Iinvestigative Committee (2006) *Investigative commission of concept of Mizusawa Geodetic Observatory,* Geospatial Information Authority of Japan (in Japanese).

Ji, X., Utsugi, M., Shirai, H., Suzuki, A., He, J., Fujiwara, S., & Fukuzaki, Y. (2006b) Modeling of spatial-temporal changes of the geomagnetic field in Japan. *Earth Planets Space 58*, pp 757-763.

Ji, X., Utsugi, M., Shirai, H., Suzuki, A., He, J., Hamazaki, H., & Amemiya, H. (2007) Modeling of the Spatial Distribution of the Geomagnetic Field in Japan with Spherical Cap Harmonic Analysis. *Journal of Geodetic Society of Japan 53* (1), pp 13-24 (in Japanese).

Shirai, H., Nishiki, T., Sato, H., Utsugi, M., Nakai, H., Morita, M., Kadowaki, T., & Yutsudo, T. (2002) Magnetic Charts for the Epoch 2000.0. *Journal of the Geospatial Information Authority of Japan 99*, pp 1-8 (in Japanese).

Ueda, I., Abe, S., Goto, K., Ebina, Y., Ishikura, N., & Tanoue, S. (2012) Geomagnetic charts for the epoch 2010.0. *Journal of the Geospatial Information Authority of Japan 123*. Retrieved September 26, 2012 from the World Wide Web: http://www.gsi.go.jp/common/000065852.pdf (in Japanese).