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A study of changes in the Earth's magnetic field in Poland in the years 1954–2017; reducing the archival values of magnetic declination at the points of the magnetic network to a uniform epoch

Elzbieta Welker
Institute of Geodesy and Cartography, 27 Modzelewskiego St., 02-679, Warsaw, Poland
Tel.: +48 22 3291913, Fax: +48 22 3291950, E-mail: email: elzbieta.welker@igik.edu.pl
ORCID: https://orcid.org/0000-0003-4373-367X

Anna Jedrzejewska
Institute of Geodesy and Cartography, 27 Modzelewskiego St., 02-679, Warsaw, Poland
Tel.: +48 22 3291913, Fax: +48 22 3291950, E-mail: email: anna.jedrzejewska@igik.edu.pl
ORCID: https://orcid.org/0000-0003-2887-5602

Abstract: At the turn of the 1980s and 1990s, the Institute of Geodesy and Cartography developed a method of reducing magnetic declination based on 40-year long magnetic observations at repeat stations. This method assumed that changes in the magnetic field at repeat stations can be described using the polynomial of the 3rd degree as a function of the position of the point (φ, λ) and the measurement epoch. The Earth's magnetic field as a temporal-spatial physical phenomenon of a variable, unpredictable nature is, however, difficult to model in a longer period of time.

At the turn of the centuries the magnetic declination values at the points of the magnetic network were reduced to the 2000.5 epoch using the polynomial function for field modelling, based on the analysis of the actual changes in magnetic declination at repeat stations and in magnetic observatories. The unified set of points of the magnetic network with declination reduced to the 2000.5 epoch constituted the base for further studies of geomagnetic field.

In the last dozen or so years, the network of the magnetic points has been updated by the new measurements of magnetic declination at over 300 points. Not all previous locations were suitable for re-measurements. In this case, a point in the nearby region that met the conditions for magnetic measurements was selected. New points, with the values of magnetic declination reduced to the measurement epoch, updated and expanded the data bank. An analysis of the course of actual changes in the Earth's magnetic field in the observatories of Central Europe and at the repeat stations of the national magnetic control of Poland from the measurement epoch, i.e. from the 1950s to the current epoch, made it possible to unify the set with points with the magnetic declination determined. From now all the points will have the value of declination assigned to the 2017.5 epoch. Thus, the procedure for the reduction of magnetic data to subsequent epochs will be simplified. The decision about the possible re-updating of the data will be taken after analysing the course of further changes in the Earth's magnetic field in Central Europe from the 2017.5 epoch.

Keywords: Earth's magnetic field, magnetic network of Poland, secular changes of the Earth's magnetic field, reduction of magnetic declination

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1. Introduction

Changes of the Earth's magnetic field (a temporal-spatial physical phenomenon) depend on:

– the position and module of the central dipole associated with the chemical composition of the internal core and the speed of its rotation relative to the rotation axis of the Earth,
– the position and module of other internal dipoles located around the Earth's core,
– external factors such as the phenomena occurring in the ionosphere and magnetosphere under the influence of the Sun, the Moon and other planets,

and they cannot be modelled. They are treated as random changes in terms of both their speed and size. This is confirmed by the results of the study of changes in the position and value of the central dipole module and other internal dipoles over a period of one hundred years (1900–2000). The changes in the Earth's magnetic field generated by them are unpredictable in a longer period of time (e.g. 10–20 years) (Demina et al., 2006).

In 2003, as part of the MagNetE (Magnetic Network For Europe) project, joint action concerning magnetic measurements at repeat stations in 20 European countries was undertaken. The results of the observations are used as a basis for the studies of the spatial and temporal changes in the Earth's magnetic field in Europe and for the development of current magnetic maps for this area (Korte, 2011). A comparison of the course of the contour lines of elements of the Earth's magnetic field obtained from the IGRF (International Geomagnetic Reference Field) model and from the results of the absolute magnetic measurements at the repeat stations of national magnetic control shows large discrepancies, especially in the anomalous regions of, for example, Poland, Lithuania and Belarus. This confirms the justness of the continuation of systematic absolute measurements at the repeat stations in Europe (Sas-Uhrynowski and Welker, 2009). Updating magnetic data always requires information about the normal magnetic field and the course of changes in the Earth's magnetic field in the studied area (Welker and Żółtowski, 1993b) between the measurement epoch and the study epoch.

The analysis of the course of the actual changes of magnetic declination in Poland in the years 1954–2017, based on the data from magnetic observatories and from repeat stations, will make it possible to unify – reduce to one, current 2017.5 epoch – all the values of magnetic declination obtained as a result of measurement in different epochs, at the points of the magnetic network of Poland (Welker, 2013), which is part of the magnetic database of the Institute of Geodesy and Cartography.

2. Historical outline

In the 1950s, the first magnetic network was established in Poland at over 3000 points located all over the country, with a density appropriate for the occur-

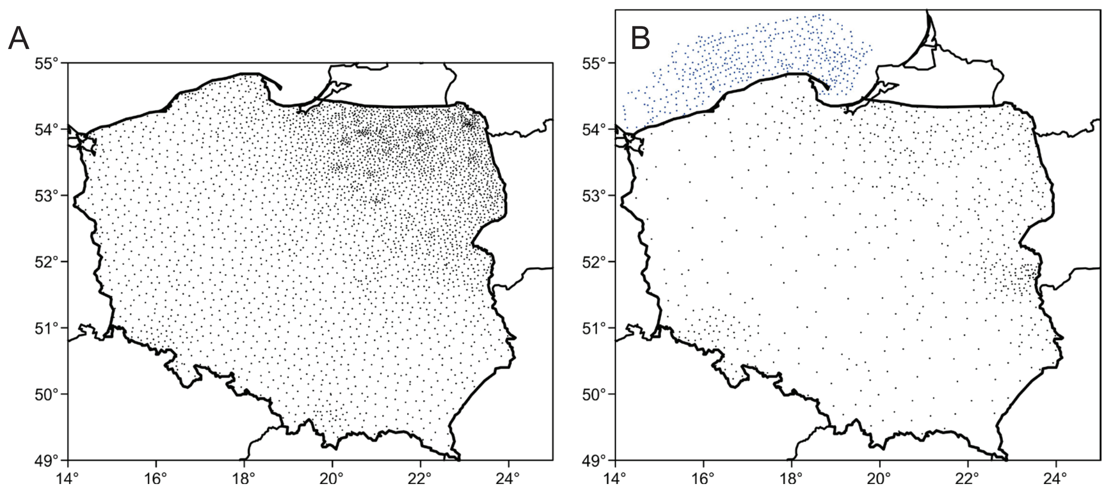

Fig. 1. Points of the magnetic network from the years 1954–1959 a); points of absolute magnetic measurements from 1965, and from the marine magnetic measurements from the years 1971–1990 b)

rence of magnetic anomalies (Fig. 1a). Magnetic declination and the position of the Sun, necessary to determine geographical azimuths of target points were measured at the network points. The points were stabilized only with wooden stakes. In 1965, a full measurement of all three components of the geomagnetic field was repeated at over 500 selected points of the network (Fig. 1b). At the same time, a national magnetic control was created with 20 repeat stations evenly distributed across the country (Fig. 2). These are points which are permanently stabilized in the field, in the places of magnetic "calmness" (without any local anomalous disturbances), at which absolute magnetic measurements of the three independent components of the Earth's magnetic field should be systematically repeated. The values of the magnetic declination calculated for the points of the magnetic network and the knowledge of the secular changes in the magnetic field determined from the measurements made at the repeat stations constitute the starting material for the analytical and graphic works related to the study of magnetic data.

In 1990, absolute magnetic measurements on the Baltic Sea were completed, and the results from their study, attached to the geophysical database of IGiK (Fig. 1b), broadened significantly the area covered by magnetic measurements (Welker, 2013).

At the turn of the 1980s and 1990s, a team of IGiK developed a method of reducing magnetic declination based on 40-year long observations at repeat stations (Welker and Żółtowski, 1993a). This method assumed that changes in the magnetic field at repeat stations can be described by means of the polynomial of the 3rd degree, which is a function of the position of the point (φ, λ) and the measurement epoch. The studies were conducted according to the formula:

$$f(\varphi, \lambda, t) = a_1\varphi^2 + a_2\lambda^2 + a_3\varphi\lambda + a_4\varphi + a_5\lambda + a_6 + \\ + (a_7\varphi^2 + a_8\lambda^2 + a_9\varphi\lambda + a_{10}\varphi + a_{11}\lambda + a_{12}) \cdot t + \\ + (a_{13}\varphi^2 + a_{14}\lambda^2 + a_{15}\varphi\lambda + a_{16}\varphi + a_{17}\lambda + a_{18}) \cdot t^2 \quad (1)$$

where φ, λ are the coordinates of the repeat station in the WGS-84 system, t is the measurement epoch, and a_i are coefficients to be determined.

For practical purposes, a local system with the initial coordinates φ_0 = 52° and λ_0 = 19° and zero

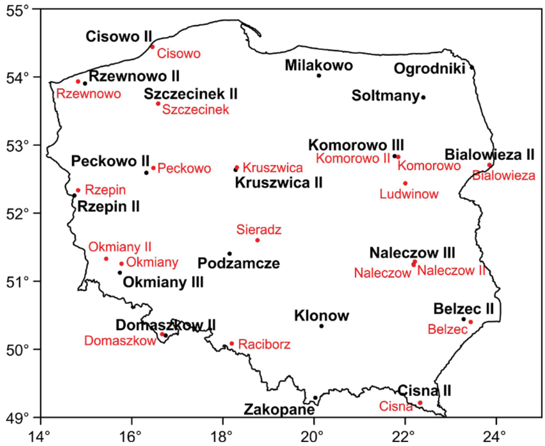

Fig. 2. Points of the national magnetic control (repeat stations) – archival points are marked in red

epoch t_0 = 1974 was adopted, which translated into the final system of equations $f(x, y, t')$:

$$f(x, y, t') = a_1x^2 + a_2y^2 + a_3xy + a_4x + a_5y + a_6 + \\ + (a_7x^2 + a_8y^2 + a_9xy + a_{10}x + a_{11}y + a_{12}) \cdot t' + \\ + (a_{13}x^2 + a_{14}y^2 + a_{15}xy + a_{16}x + a_{17}y + a_{18}) \cdot t'^2 \quad (2)$$

where $x = (\varphi - \varphi_0)/dx$, $y = (\lambda - \lambda_0)/dy$, $t' = (t - t_0)/dt$, dx, dy are the absolute values of coordinate differences between the border points of the area and the centre of the local system in degrees, and dt is the difference of years between the initial epoch and the epoch adopted as zero.

Additionally, the equations were weighed depending on the distance of the point from the centre of the local system.

After appropriate calculations, a normal magnetic field for the area of Poland was obtained (Welker and Żółtowski, 1993b), which was used for the reduction of magnetic data and for calculating magnetic anomalies.

After reducing the magnetic declination at the points of the magnetic network of Poland to the 2000.5 epoch based on the actual changes of magnetic declination in observatories and at repeat stations, and using the polynomial function, it was possible to compare the results. The contour lines are presented on the map of the magnetic declination of Poland for the 2000.5 epoch developed using various methods (Fig. 3). Differences between them are below annual change of magnetic declination. Consequently, for further studies of geomagnetic field, the grids created for the study epoch and the 2000.5 initial epoch can be used, according to the formula (3)

$$D_{ep} = D_{mes} + (ep - ep_0)\Delta d + \Delta D \qquad (3)$$

where D_{ep} and D_{mes} are the value of declination at a point of the magnetic control calculated for the study epoch *ep*, and measured at epoch ep_0, respectively, Δd is the value of the annual change in the declination obtained from the grid of changes calculated in relation to the Observatory in Belsk, which is a function of the location of the point, and ΔD is the difference of the change in declination in Belsk between the study epoch *ep* and the measurement epoch ep_0.

To verify the reduction calculations (formulae 1–3), repeat stations with the magnetic declination values obtained from the absolute geomagnetic measurements from the year 2000 were marked on the map (Fig. 3).

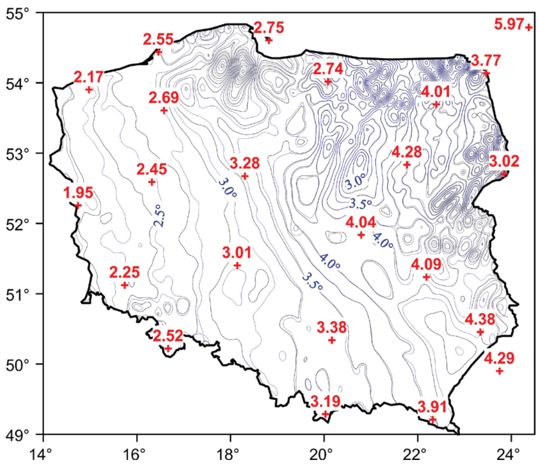

Fig. 3. The contour lines of the magnetic declination of Poland at the 2000.5 epoch developed using the polynomial function (blue colour) and the actual change grids (black colour) with marked repeat stations and the values of the magnetic declination determined on them (red colour)

3. Current studies

Magnetic measurements at the repeat stations of the national magnetic control are conducted systematically every 2–3 years, and this is automatically associated with the expansion of the magnetic database bank. After more than 60 years which have passed since the first measurements of the magnetic declination at the points of the magnetic network of Poland and the absolute measurements in magnetic observatories and at repeat stations, data allowing to perform an in-depth analysis of changes in the Earth's magnetic field in Poland during that period were collected. The use of new measuring equipment and new computational techniques makes it possible to apply another method for the interpolation and extrapolation of the value of magnetic declination at measurement points, and for its conversion into one selected epoch.

At the beginning of the 21st century, verification measurements of magnetic declination were made at over 300 selected points of the magnetic network. Many of them, due to the changes in the infrastructure of the surroundings, had to be moved to the nearest place convenient for conducting measurements. Due to the inconsistencies with

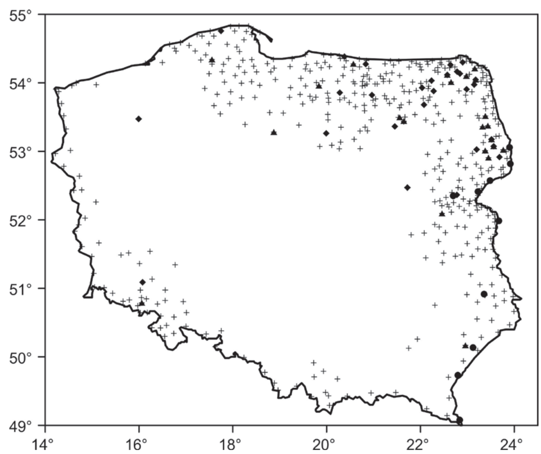

Fig. 4. Verified and new points of the magnetic network of Poland from the years 2002–2004 (crosses), 2008 (triangles), 2012–2013 (diamonds) and 2017 (circles)

archival data that emerged during the analysis of the obtained results, the magnetic measurements were repeated at about 30 points of the magnetic network. Gradually, as far as possible, the magnetic network was expanded to include new points, among others, points from the marine magnetic measurements conducted on the Baltic Sea in the years 1971–1990 (Fig. 1b) (Sas-Uhrynowski et al., 2000). Due to the absence of magnetic data from Belarus and Ukraine, and the large anomalousness of the north-eastern areas of Poland, particular attention was paid to the densification of the regions of the eastern border of Poland with magnetic points (Fig. 4). Magnetic data from the areas of Germany, the Czech Republic and Slovakia are available and make possible the good interpolation of contour lines in border areas.

The complexity and variability in time of the Earth's magnetic field in Poland can be illustrated, for example in Figure 5, showing the changes in magnetic declination at the six oldest repeat stations and in magnetic observatories – Belsk and Hel, where magnetic measurements have been systematically conducted since the 1950s. Figure 5 also shows the approximation lines of the course of declination at selected time intervals, which were used to final reduction of magnetic declination to the 2017.5 epoch.

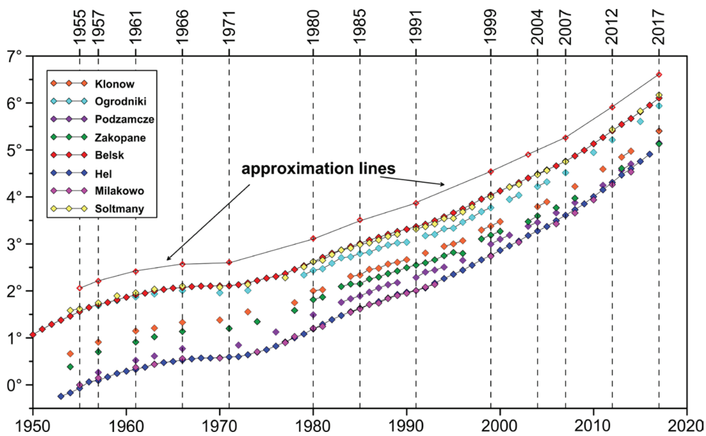

Fig. 5. The course of the magnetic declination in the magnetic observatories in Belsk and Hel, and at selected repeat stations

4. The aim of the work

The aim of the work was to reduce the value of the magnetic declination at the points of the magnetic network of Poland from the years 1954–2017 to the current 2017.5 epoch, based on the analysis of the course of the real changes in the Earth's magnetic field from the measurement epoch, i.e. from the 1950s. This will make it possible to unify the initial base of magnetic declination (all points will have the current value assigned to the 2017.5 epoch) and, thus, to simplify the procedure of data reduction to subsequent epochs. In this way, errors related to the calculation of the reduction values for longer and longer time intervals will be avoided.

The analysis was carried out on the basis of the magnetic observations from all the repeat stations of the national magnetic control and the results from the magnetic observatories of Poland and neighbouring countries.

Figure 5 shows that the course of the changes in magnetic declination in the years 1954–2017 at all of the selected points is analogous. In the years 1954–1966, the shape of the line of changes in magnetic declination is parabolic. In subsequent years, these changes can be presented as linear functions, with varying inclination. Based on the course of the magnetic declination registered at the Central Geophysical Observatory of IGF PAN in Belsk, and on the basis of known measurement epochs, the following time intervals were selected for the study at the points of the magnetic network: 1955–1957, 1957–1961, 1961–1966, 1966–1971, 1971–1980, 1980–1985, 1985–1991, 1991–1999, 1999–2004, 2004–2007, 2007–2012, 2012–2017.

In order to develop isopor maps, it is necessary to know the value of the magnetic declination at the repeat stations for the epochs constituting the limits of selected intervals. In the case when, in a selected year, no measurements were performed at a repeat station, the declination value was approximated on it by means of the linear interpolation between the values measured at this point in the surrounding years. In case of doubts as to the quality of the approximated values, they were verified by analysing the courses of magnetic declination in the magnetic observatories of Central Europe. Next, differences of magnetic declination in selected time intervals and the annual increment of declination in selected periods were calculated.

For selected time intervals, isopor maps (lines of annual changes in magnetic declination) were developed, for example those presented in Figure 6.

Studies of the secular changes in the Earth's magnetic field are conducted throughout Europe. Satellite data or data obtained from global magnetic field models (IGRF) are mainly used for this purpose (Korte, 2011). Poland is one of the few countries in possession of a database with absolute magnetic measurements at repeat stations since the 1950s, which in combination with data from magnetic observatories is an invaluable source used to study local changes in the geomagnetic field (Schultz et al., 1997).

The courses of isopors developed by the authors (Fig. 7) have different shapes and values. They show how the secular changes in this period are unpredictable and how unpredictable local disruptions can be. A certain constant trend of changes in magnetic declination can be observed, over a longer period of time, from the west to the north-west, and a clear upward trend in their value (Jędrzejewska and Welker, 2011). Isopor maps were developed in Central Europe in the years 1980–2005 (Fig. 7), and their analysis showed similar trends (Welker, 2007).

Based on the isopor maps developed for selected intervals, values of magnetic declination changes were generated at 0.01°×0.01° grid nodes. The magnetic declination values at the points of the magnetic network measured in different epochs were reduced to the epochs constituting the extreme year of the interval. To this end, the value of the

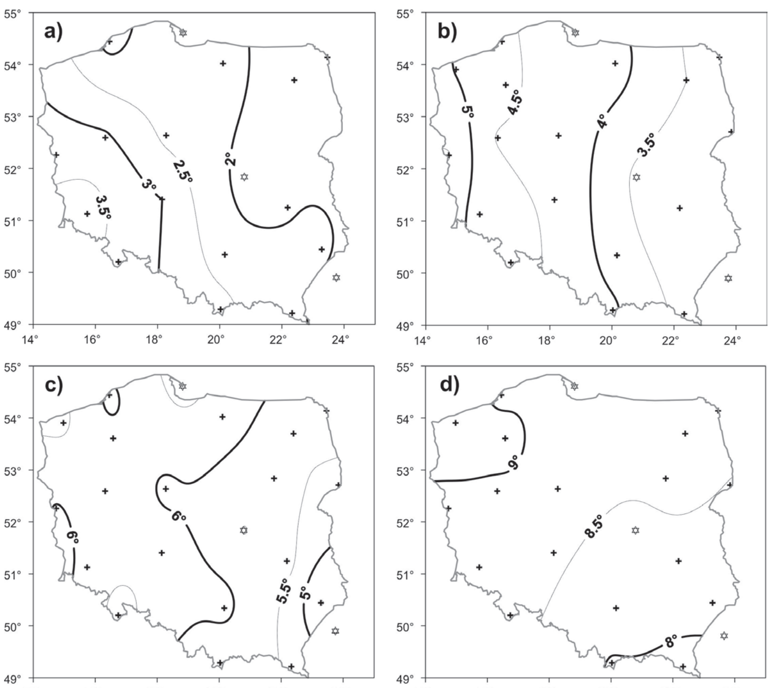

Fig. 6. Maps of magnetic declination isopors in Poland in the years: a) 1957–1961, b) 1980–1985, c) 1999–2004, d) 2012–2017

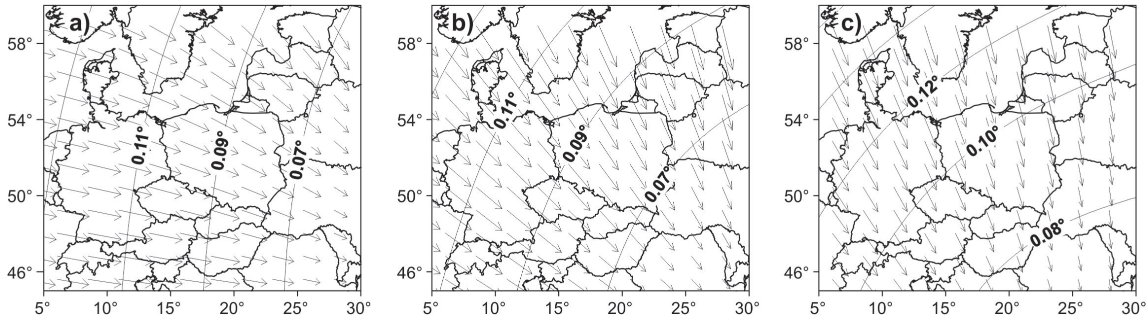

Fig. 7. Directions of changes in the magnetic declination in Central Europe in the years: a) 1980–1990, b) 1990–2000, c) 2000–2005

annual increment from the grid node located closest to the point, multiplied by the number of years from the moment of measurement to the extreme year of the given period, was added to the declination value measured at each point. In this way, sets of points with the values of magnetic declination reduced to the 1957, 1961, 1966, 1971, 1999, 2004, 2007, 2012 epochs (base values) were obtained. In addition, multiple measurements were verified at the same points. Extreme values were rejected and repetitive values were averaged. In order to reduce base declination values to the 2017.5 epoch, similarly to the previous actions, the differences between the magnetic declination at the selected epoch and the 2017.5 epoch, at repeat stations and in the magnetic observatories of Poland as well as neighbouring countries, were calculated. Next, eight 0.01°×0.01° grids were generated from them in the digital form required for further study. The final values of the magnetic declination for 2017.5 epoch at the points of the magnetic network were obtained by adding the value read from the node closest of the point from an appropriate grid to the base values (measurement values).

5. Results

Elaborating maps of the magnetic declination for the 2017.5 epoch on the basis of the values of declination at the points of the magnetic network from:

– the base reduced at the beginning of the century to the 2000.5 epoch, and recalculated to the 2017 epoch on the basis of changes at repeat stations and in magnetic observatories (Fig. 8 – black lines),
– the reduction of archival and modern measurement results to the 2017.5 epoch based on the analysis of the actual declination changes between the measurement epoch and the study epoch (Fig. 8 – red lines)

and comparing the courses of contour lines made it possible to verify the developed set.

Additionally putting the repeat stations with the values of magnetic declination measured directly at a point in the 2017.5 epoch (Fig. 8 – navy blue crosses) on the image of contour lines confirmed the correctness of the study.

The comparison of the magnetic declination images developed for the 2017.5 epoch, based on the declination values reduced to the epoch 2000.5 at the points of the magnetic network, and based on

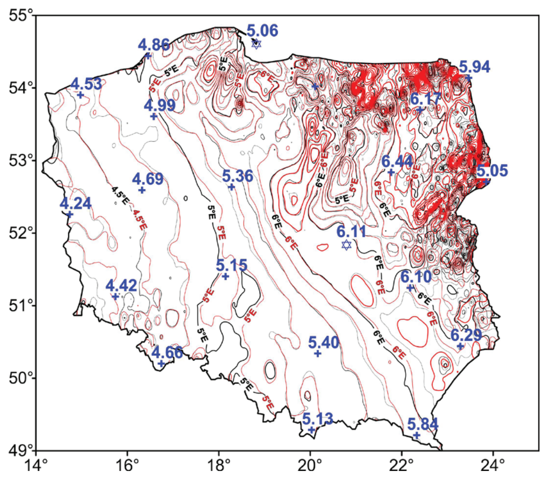

Fig. 8. Magnetic declination in Poland for the 2017.5 epoch

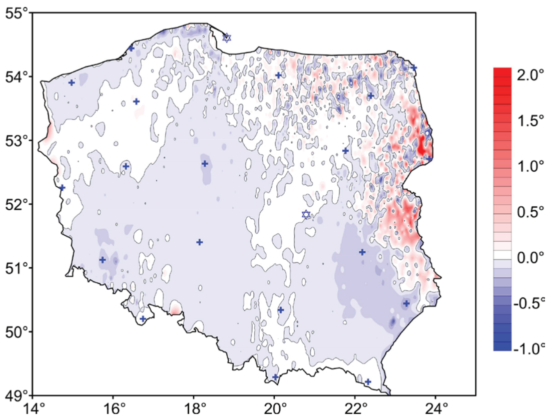

Fig. 9. Differences in the contour lines obtained from the maps of magnetic declination developed for the 2017.5 epoch on the basis of the declination values reduced to the epoch 2000.5 at the points of the magnetic network, and based on declination values referred to the observation epoch (repeat stations are marked with crosses)

declination values referred to the observation epoch (Fig. 9), shows good matching of the contour lines in the western and central Poland (the differences do not exceed 10′) and discrepancies reaching one degree in declination in areas of strong anomalies.

Taking into account some limitations of the methods used in the previous century and the fact of extending the database to include new points of the magnetic network located in anomalous and border regions (in the current century), the results of the comparison can be considered as satisfactory (Fig. 10). Only at two repeat stations located in the east of Poland, i.e. Belzec and Naleczow, the differences between both studies exceeded 10’. Images of the magnetic anomalies in the north-eastern region of Poland, in the studied epochs, show significant differences in both values and shapes. The densification of measurement points in the anomalous area in the years 2002–2017 made it possible to determine more accurately the location of magnetic declination anomaly; the differences reached the level of one degree.

6. Summary and conclusions

The creation of a current, unified database with the points of the magnetic network and the values of magnetic declination reduced to the 2017.5 epoch assigned to them, simplifies all further magnetic studies, i.e. the reduction of the declination values at the measurement points, or the creation of magnetic maps for the desired epoch. The use of unified data makes it possible to avoid errors related to the transfer of values of magnetic declination from distant measurement epochs to the current study epoch.

It should be noted that in areas of strong magnetic anomalies, the exact value of magnetic declination at a particular point can only be obtained from direct measurements. When estimating this value from the map, one should expect an error of even above one degree.

The results of the study of absolute magnetic measurements at the repeat stations of the national magnetic control are sent to the magnetic World Data Centre (WDC) in Edinburgh, and are used to develop a global model of the Earth’s magnetic field.

The next step in the study of local secular changes in the Earth’s magnetic field should be the analysis of the differential magnetic field changes obtained from the regional and global (normal) models using the appropriate modelling type (Mandea and Korte, 2011). It should be expected that these changes in Poland will not be systematic in nature. They may depend on the changes in the magnetization in the Earth’s crust, on the changes in the magnetic field in the ionosphere, as well as on some local disturbances not related to the magnetic field, but affecting its values.

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Opracowanie zmian pola magnetycznego Ziemi w Polsce w latach 1954–2017; redukcja archiwalnych wartości deklinacji magnetycznej na punktach zdjęcia magnetycznego do jednolitej epoki

Elżbieta Welker
Instytut Geodezji i Kartografii, ul. Modzelewskiego 27, 02-679, Warszawa
Tel.: +48 22 3291913, Fax: +48 22 3291950, E-mail: email: elzbieta.welker@igik.edu.pl
ORCID: https://orcid.org/0000-0003-4373-367X

Anna Jędrzejewska
Instytut Geodezji i Kartografii, ul. Modzelewskiego 27, 02-679, Warszawa
Tel.: +48 22 3291913, Fax: +48 22 3291950, E-mail: email: anna.jedrzejewska@igik.edu.pl
ORCID: https://orcid.org/0000-0003-2887-5602

Streszczenie: Na przełomie lat 80. i 90. XX w. w Instytucie Geodezji i Kartografii opracowano metodę redukcji deklinacji magnetycznej na podstawie 40-letnich obserwacji magnetycznych na punktach wiekowych. Metoda ta zakładała, że zmiany pola magnetycznego na punktach wiekowych dadzą się opisać za pomocą wielomianu 3-go stopnia w funkcji położenia punktu (φ, λ) oraz epoki pomiaru. Pole magnetyczne Ziemi jako czasowo-przestrzenne zjawisko fizyczne o zmiennym, nieprzewidywalnym charakterze jest jednak trudne do zamodelowania w dłuższym okresie czasu.

Na przełomie wieków wykonano redukcję zbioru zdjęcia magnetycznego do epoki 2000.5 na podstawie analizy rzeczywistych zmian deklinacji magnetycznej na punktach wiekowych i w obserwatoriach magnetycznych wykorzystując funkcję wielomianową do modelowania pola. Utworzony w ten sposób jednolity zbiór punktów zdjęcia magnetycznego zredukowany na epokę 2000.5 stanowił bazę wyjściową do dalszych opracowań magnetycznych.

W ciągu ostatnich kilkunastu lat zaktualizowano sieć zdjęcia magnetycznego poprzez nowe pomiary deklinacji magnetycznej na ponad 300 punktach. Nie wszystkie poprzednie lokalizacje nadawały się na miejsca ponownego pomiaru. W takim wypadku wybierano w pobliskim rejonie punkt spełniający warunki dla pomiarów magnetycznych. Nowe punkty ze zredukowanymi wartościami deklinacji magnetycznej na epokę pomiaru zaktualizowały i rozszerzyły bank danych. Analiza przebiegu rzeczywistych zmian pola magnetycznego Ziemi w obserwatoriach Europy Środkowej oraz na punktach wiekowych podstawowej osnowy magnetycznej Polski od epoki początkowej pomiarów, tj. od lat 50. ubiegłego wieku do epoki bieżącej, umożliwiła ujednolicenie zbioru z punktami zdjęcia magnetycznego i wyznaczonymi na nich wartościami deklinacji; wszystkie punkty będą miały aktualną wartość przypisaną do epoki 2017.5. Uprości się tym samym procedura redukcji danych do następnych epok. Decyzja o ewentualnym, ponownym zaktualizowaniu zbioru zostanie podjęta po przeanalizowaniu przebiegu dalszych zmian pola magnetycznego Ziemi na terenie Europy Środkowej od epoki 2017.5.

Słowa kluczowe: pole magnetyczne Ziemi, zdjęcie magnetyczne Polski, zmiany wiekowe pola magnetycznego Ziemi, redukcja deklinacji magnetycznej