

On the validation of K index values at Italian geomagnetic observatories

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Abstract. Local K index and the consequent global Kp index are well established three-hour range indices used to characterize the geomagnetic activity. K index is one of the parameters which INTERMAGNET observatories can provide and it's widely used since several decades, although many other activity indices have been proposed in the meanwhile. The method for determining the K values has to be the same for all observatories. INTERMAGNET consortium recommends the use of one of the 4 methods endorsed by the International Service of Geomagnetic Indices (ISGI) in close cooperation and agreement with the ad-hoc working group of International Association of Geomagnetism and Aeronomy (IAGA). INTERMAGNET provides the software code KASM, designed for an automatic calculation of K index according to the Adaptive Smoothed method. K values should be independent on the local dynamic response, therefore for their determination each observatory has its own specific scale regulated by the L9 lower limit, which represents the main input parameter for KASM. The determination of an appropriate L9 value for any geomagnetic observatory is then fundamental. In this work we statistically analyze the K values estimated by means of KASM code for the Italian geomagnetic observatories of Duronia (corrected geomagnetic latitude $\lambda \sim 36^\circ$ N) and Lampedusa ($\lambda \sim 28^\circ$ N) comparing them with the German observatories of Wingst and Niemegk. Our comparative analysis is finalized to establish the best estimation of the L9 lower limit for these two stations. A comparison of L9 lower limits found for the Italian observatories with results from a previous empirical method was also applied and used to verify the consistency and reliability of our outcomes.

1 Introduction

In their pioneering work, Bartels et al. (1939) introduced the three-hour-range K index with the purpose of quantifying the solar wind (or particle) effects on the geomagnetic field. K index is represented with an integer in the range 0–9 (“K” is from the German word Kennziffer meaning “characteristic digit”) with 0 and 1 being an indication of quiet condition and 5 or more referring to an increased level of magnetic activity, generally related to a geomagnetic storm. It is derived for a specific observatory from the maximum fluctuations of horizontal components observed on a magnetogram during a three-hour interval, evaluated as difference between maximum positive and negative deviations with respect to a reference curve which essentially reflects the local diurnal variation at the observatory. These maximum deviations may occur at any time during the 3 hour period. The proposed K index was originally calculated for Niemegk observatory.

As a natural consequence of K index, the planetary geomagnetic activity index Kp was proposed by Bartels (1949). It is derived from the standardized K index (Ks) of 13 magnetic observatories at mid latitude and it is representative of the large spatial-scale of the solar wind-magnetosphere coupling energy. Therefore, K index is the fundamental parameter for Kp estimation; Kp, as any other index, has limitations and drawbacks; however, it's precious since it's an historical parameter and long data series are available; it is widely used, for example, in space weather applications, for identify quietest days (Johnston, 1943) used also in the IGRF modeling, for verifying solar wind driven modulation in the atmospheric parameters during disturbed conditions (Regi et al., 2017).

The main difficulty for K indices evaluation is to assign a proper quasi-logarithmic scale to the geomagnetic fluctuations that satisfy the principle of the assimilation of frequency distributions (AFD): the frequency distributions (or occurrences) of K index values at different sites are, in principle, the same (Bartels et al., 1939). In other words, A values vary from observatory to observatory in such a way that the historical rate of occurrence of certain levels of K is about the same at all observatories (Bartels-Mayaud rules). This implies that, for a given K value, A_K increases with increasing latitude, and the fundamental quantity for the K index calculation is represented by the minimum amplitude L9 corresponding to K=9, from which also the other A_K values are derived.

For Kp determination (Bartels et al., 1939), from higher to lower latitude, at Sitka (AACGM latitude $\lambda \sim 60^\circ$ N, Alaska, Alaska), L9 =1000 nT while Canberra (AACGM latitude $\lambda \sim 45^\circ$ S, Australia), L9 =500 nT. The GFZ website (<https://www.gfz-potsdam.de/en/kp-index/>) provides the 13 L9 values used for the Kp evaluation, showing values between 450 nT and 1500 nT; in particular, at Niemegk (AACGM latitude $\lambda \sim 48^\circ$ N, Germany) L9=500 nT. In the present manuscript all the AACGM coordinates are computed by using the Shepherd (2014) algorithm, applied to year 2017.

The original determination of K indices (Bartels et al., 1939) required hand scaling of analogic magnetograms. For many years, K index was in fact manually scaled by visual determination and removal of the regular daily variation; the remaining largest amplitude of geomagnetic disturbances in the two horizontal components during each 3-hour UT interval, was used to determine the K index values from a conversion table between classes of ranges in nT and K indices.

The question of the derivation of geomagnetic indices from digital data arose at the end of the seventies of the last century. Different algorithms enabling computer derivation of K indices were then developed and carefully assessed in the frame of an international comparison organized by the IAGA Working Group "Geomagnetic indices" (Coles and Menvielle, 1991; Menvielle, 1991; Menvielle et al., 1995).

This implies the production of computer plots of digital data with scale values similar to those of photographic magnetograms (Menvielle et al., 1995). The International Association of Geomagnetism and Aeronomy (IAGA, <http://www.iaga-aiga.org/>) promotes tools or methods able to make it easier to keep track of files and analyses done on computers.

Different methods were proposed and carefully compared and assessed in occasion of an international meetings organized by the IAGA Working Group “Geomagnetic indices” during the Vienna IUGG general Assembly in 1991 and four methods
65 were acknowledged: FMI (provided by Finnish Meteorological Institute, Finland), LRNS (Hermanus Magnetic Observatory, CISR, South Africa), KASM (Institute of Geophysics, Polish Academy of Science) and USGS (USGS, USA), whose Fortran
77 codes are available at the International Service of Geomagnetic Indices (ISGI, <http://isgi.unistra.fr/software.php>).

We used one of the 4 methods endorsed by IAGA, through the ISGI international service, for calculation of local geomagnetic activity indices K and, in particular, the KASM method that is based on adaptive smoothed method
70 (Nowozyński et al., 1991). For the calculation of the K index, IAGA formatted files are used by KASM code. It requires three daily files, the one under analysis and the files of the previous and following days on which the code estimates the regular daily variation. The code also needs as input parameters the L9 value and the yearly average of the H component relative to the year of interest.

We want to point out that it does not exist a unique L9 at a given geomagnetic latitude since each site might be affected by
75 different local features such as, for example, crustal anomalies (Chiappini et al., 2000) and/or coast effect (Parkinson, 1962; Regi et al., 2018). Moreover, there is the inevitable MLT dependencies of magnetic disturbances which can be smoothed out through statistical approach, considering long time observations. For the inclusion of a new geomagnetic observatory into the INTERMAGNET network, an L9 value can be initially assigned according to the ISGI indication but it can be refined by comparing long term geomagnetic field variations at the new observatory and at historical ones for which K indices are
80 estimated by using well defined L9 levels.

We used the geomagnetic data from the two Italian geomagnetic observatories at Duronia (DUR) and Lampedusa (LMP), evaluating the K index with the purpose of estimating the best L9 value for each observatory.

DUR observatory is operating in Central Italy in the area of the village of Duronia (geogr. coordinates: 41°39’N, 14°28’E, 910 m a.s.l.). It was installed at the end of 2007 in the framework of MEM (Magnetic and Electric fields Monitoring) Project
85 that aims to investigate the environmental electromagnetic signals in the ULF-VLF (0.001 Hz - 100 kHz) frequency band, and was granted as geomagnetic observatory in 2012, when it was included in the INTERMAGNET network (<http://www.intermagnet.org>), replacing the historical geomagnetic observatory at L’Aquila partially damaged after the local M_w 6.2 earthquake in 2009.

LMP is the southernmost observatory in European territory (geogr. coordinates: 35°31’N, 12°32’E); it was installed in 2005
90 and is regularly working since 2007.

Up to now, K index was evaluated only for DUR observatory, using $L9=350$ nT, both for hand-scaling (since 2012) and for KASM program (since 2017).

In this work we evaluated L9 throughout a correlation analysis performed between K index at DUR with that provided by historical observatories. In order to take into account the magnetic local time dependency of reference K index, European observatories were selected. As possible reference observatories we chose Wingst (WNG) and Niemegek (NGK), since they are among the 13 observatories that contribute to the Kp estimation and their local magnetic time is quite close to that of our Italian observatories.

Our investigations suggest that NGK is the best reference observatory for Italian geomagnetic observatory of DUR, probably due to the closest magnetic local times: indeed the amplitude of magnetic disturbances has dependence on (magnetic) local time which affects the K index values (Chambodut et al. (2013)). By comparing DUR with NGK we estimated a reliable DUR L9 level of 320 nT. Finally, by comparing also LMP with NGK, a reliable LMP L9 level of 310 nT is estimated.

2 Data and methods of analysis

Geomagnetic field variations at Italian geomagnetic observatories of DUR and LMP are measured by using three-axis fluxgate magnetometers along the northward (H), eastward (D), and vertically downward (Z) directions in the geomagnetic reference frame at 1 s sampling rate. Following the INTERMAGNET directives, geomagnetic time series are also stored as daily archives at 1 min sampling rate, according to the IAGA 2002 format.

In this work we used minute data computed from second data using INTERMAGNET 1s to 1min filter, available in the time interval 1 January 2017 – 31 December 2018, a temporal window which falls in the lower part of the sunspot number curve for the cycle 24 (Upton & Hathaway, 2018).

These data are used for estimating K indices by using KASM algorithm which is recommended by INTERMAGNET. In this work, the definitive L9 level at DUR is empirically estimated throughout the following procedure:

- a) we selected a reference observatory;
- b) K index time series at DUR are computed by using KASM for different L9 values (K_{L9}) in the range 200-400 nT with a step size of 10 nT;
- c) each K_{L9} index time series at DUR is compared with K index time series at reference observatory through correlation analysis;
- d) the definitive L9 level at DUR is estimated in correspondence of the maximum correlation coefficient.

As possible reference we selected the historical observatories of NGK and WNG since they are among the 13 observatories used for Kp evaluation, they are both in Europe at a MLT close to that of DUR and LMP (see Tab.1 and Fig.1), which is at the moment the principal Italian observatory, member of the INTERMAGNET network and then used in this work as

reference observatory for any Italian site. By following our procedure at point c), using independently NGK and WNG, we found that the higher correlation is reached with NGK. The same procedure from a) to d) is applied to the lower latitude Italian observatory of LMP.

125 We note that K indices at NGK and WNG are both generated by using FMI algorithm. Then, we find useful to verify that FMI and KASM are consistent methods by comparing K values estimated with both methods at NGK.

Finally, we compared L9 values estimated at Italian geomagnetic observatories by means of our method, with those estimated using an historical method proposed by Mayaud (1980).

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3 Experimental results

3.1 L9 empirical estimation

We retain that it is important to know how K indices are distributed at consolidate reference observatories of NGK and
135 WNG and how they are in relation to each other.

Figure 2 shows the K index at NKG (panel a) and WNG (panel b) and the difference $\Delta K = K_{\text{NGK}} - K_{\text{WNG}}$ (panel c) during 2017-2018; it also shows (panel d) the K index frequency distributions ν (or occurrences) at the two observatories. We can see that the two frequency distributions are very close, as confirmed by the distribution of ΔK (panel f), with the largest number of cases in correspondence of $\Delta K = 0$ (4680 cases, ~80%), and by the absence of cases with $|\Delta K| > 1$. However, ΔK distribution
140 shows also a non-symmetric distribution around zero, with a very different number of cases in correspondence of $\Delta K = \pm 1$: 1103 cases (~19%) for $\Delta K = -1$ and 48 cases (~1%) for $\Delta K = +1$; this feature is also evidenced by the linear regression law: $K_{\text{NGK}} = \alpha K_{\text{WNG}} + \beta$ (panel e), where by imposing $\beta = 0$ it is obtained $\alpha = 0.914 \pm 0.004$, i.e. $\alpha < 1$.

We investigated the frequency distribution ν of K at NGK in correspondence of $\Delta K = \pm 1$ cases, and compared these distributions with the general distribution of K at NGK (the one shown in Fig.2d). Figure 3 shows these distributions,
145 separately for $\Delta K = -1$ and $\Delta K = +1$ conditions during 2017-2018 (top panels), and separately for the two years (middle and bottom panels). In each panel, the K occurrences at NGK, regardless of ΔK , are superimposed (red lines). It can be seen that the general distributions of K and $\Delta K = -1$ are very similar; those of K and $\Delta K = +1$ are also quite similar, although the total number of cases is really lower. Therefore, the occurrences for $\Delta K \neq 0$ seem not to be led by particular magnetospheric activity conditions.

150 Figure 4 shows the result of the correlation analysis between K indices at Italian observatories of DUR (panel a) and LMP
(panel b) with those at NGK (red thin line) and WNG (black thin line) as functions of L9 level used by KASM for the time
interval 2017-2018. In this figure L9 levels are in the range 200-450 nT, with a step size of 10 nT. The tick lines, which
show the smoothed curves computed by using a five-points triangular window, will be used hereafter as actual experimental
155 L9=320 nT) with respect to DUR-WNG observatories ($r \sim 0.908$ for L9=290 nT). Regarding LMP, the correlation attains
lower values with respect to DUR, with maximum values of $r \sim 0.875$ for L9=310 nT with NGK, and $r \sim 0.870$ for L9=300 nT
with WNG. The lower correlations between the Italian observatories and WNG could be due to the higher latitudinal
separation and possibly to the geomagnetic coast effect at WNG.

As expected, both the L9 limit and r increase with the increasing geomagnetic latitude of referred observatory, here
160 represented by DUR and LMP. In addition, the higher correlations obtained by using NGK are probably due to the lower
latitude (i.e. closer to the Italian observatories) and the closer MLT with respect to DUR (table 1). Also at LMP, even if the
MLT is closest to that of WNG, the higher correlation is found with NGK: this result suggests that latitudinal effects are
dominant with respect to MLT ones. This can be well understood taking into account that the MLT range of all selected
observatories is within 11 minutes, well shorter than the 3-hour interval used for K determination.

165 Anyway, from these results we can assert that for the comparison with Italian observatories NGK is slightly better than
WNG, and it will be used hereafter as the reference observatory for DUR and LMP. We can also assume that the best
estimation of the L9 value at DUR and LMP is 320 nT and 310 nT, respectively; so the K indices computed by using KASM
at DUR with L9=320 nT and at LMP with L9=310 nT represent the best input parameter for the K evaluation for Italian
observatories.

170 Figure 5 shows the frequency distribution of the difference between these K-index time series and that computed at NGK.
The occurrences for both DUR and LMP are distributed around zero and in the range $[-1;+1]$. For a comparison, we show
also the difference distribution obtained for DUR using L9=350 nT (dashed blues line); we recall that this is the L9 value we
used up to now. It can be seen that, while for L9=320 nT the distribution is almost symmetric around zero, using L9=350 nT
it appears more asymmetric, unbalanced towards positive values, confirming that a higher correlation between NGK and
175 DUR is found for L9=320 nT. At LMP the distribution appears slightly asymmetric, and this discrepancy with respect to
DUR could be attributed to the larger latitudinal and MLT difference between NGK and LMP.

Since our validation procedure aims to estimate comparable K indices at Italian observatories, we found useful to compute
 ΔK between DUR and LMP, whose distribution is shown in Fig. 6. It is almost symmetric around zero, closely reflecting the
distribution of ΔK computed between K indices at LMP and NGK (from Fig.5); we can also see that $|\Delta K|$ never exceeds 1,
180 confirming the validity of the results obtained at DUR and LMP by using KASM.

It should be noted that our comparative investigation is based on K indices at reference observatories of NGK and WNG, which are computed by using FMI algorithm with L9=500 nT, while at DUR and LMP K indices are estimated by using KASM. Therefore, the question arising from our calibration method is: are FMI and KASM algorithms consistent?

In order to answer to this question, we performed a correlation analysis between K indices obtained by using FMI (K_{FMI}) and
185 KASM (K_{KASM}), where the latter K index is obtained for different L9 levels. In this regards we used NGK 1-min data, provided by the INTERMAGNET web site. Since at the moment NGK geomagnetic field measurements are stored as definitive and quasi-definitive data for 2017 and 2018 respectively, we preferred to separate the analysis for the two years.

Figure 7a shows the correlation analyses between K indices at NGK (from FMI algorithm) and that computed by KASM by using L9 in the range 350-600 nT, with a step size of 10 nT. It can be seen that, the r maxima (~ 0.96 and ~ 0.95) are reached
190 for L9=460 nT in both years. Assuming that K_{KASM} computed for L9=460 nT represents the better K indices in comparison with K_{FMI} , we examined the occurrences of $\Delta K = K_{FMI} - K_{KASM}$ (Fig.7, panels b and d). We can see that for $\sim 90\%$ of cases (and for both years) ΔK is equal to zero. Frequency distributions of K_{KASM} (460 nT) and K_{FMI} (500 nT) indices for the years 2017 (panel c) and 2018 (panel e) are also shown. We point out how the distributions are close to each other, suggesting that FMI and KASM are consistent algorithms, even if they are based on different L9 limits applied for the same observatory, in
195 agreement with Coles and Menvielle (1991), Menvielle (1991) and Menvielle et al. (1995).

3.2 Comparison with a previous L9 estimation method

As explained in the introduction, the geomagnetic indices are historically assigned throughout visual inspection of magnetograms. The main difficulty for K indices evaluation is to assign a proper value for the L9 limit from which
200 determining the quasi-logarithmic scale to the geomagnetic fluctuations in order to satisfy the AFD principle (Bartels et al., 1939). Mayaud (1968; 1980) proposed a method for calculating the geomagnetic activity level L at a given site by comparing the amplitude of geomagnetic fluctuations at the reference observatory (A_0) with that, for example, at new one (A) as follows: $L = L_0 A / A_0$, where L_0 represents the level of geomagnetic activity at the reference observatory, equivalent to L9, and all quantities are dependent on $\delta = \min[\lambda_{oval} - \lambda]$, i.e. the minimum angular separation between the site, located at
205 geomagnetic latitude λ , and the auroral region, at λ_{oval} . According to Mayaud (1968; 1980), an approximate value of δ could be given by $\delta = 69^\circ - \lambda$, where the latitude 69° in the corrected geomagnetic coordinate system defines the auroral zone.

We searched a simple relationship which relates L9 (or L) to the geomagnetic latitude of the observatory.

As showed by Mayaud (1980), L9 increases with decreasing δ ($L9 \propto \delta^{-1}$), as expected for a geomagnetic field induced by a current system. Figure 8 shows L9(δ) (blue points) provided in Tab. 5 by Mayaud (1980), considering only northern
210 hemisphere. These points are well represented by a linear law considering an increasing induction effect with increasing parameter $x = 1/\delta$.

Therefore, by using $x=1/\delta$, previous relationship is linearized and can be formulated as follows

$$L9(x) = \alpha x + \beta . \quad (1)$$

215 The results of the linear regression analysis performed on the experimental points are also reported in Fig.8.

Equation 1 is therefore useful for estimating a reasonable L9 limit at a different site. In order to evaluate L9 at DUR, LMP and, for a comparison, at NGK observatories, the corresponding δ parameter is required. However, it is not clear how δ was estimated by Mayaud (1980), since it requires, for example, an auroral oval model for estimating the λ_{oval} , and an IGRF model for evaluating the geomagnetic latitude λ of a given site (this aspect will be further discussed at the end of this section).

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In this regard, we empirically estimated $\delta(\lambda)$ by a linear fit of the experimental data reported by Mayaud (1980). Figure 9 shows experimental points (red stars) and the corresponding linear law (red line)

$$\delta(\lambda) = a\lambda + b , \quad (2)$$

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which allows us to extrapolate an estimation of the theoretical $\delta_{th}(\lambda)$ for the observatories of DUR, LMP and, for comparison at NGK too (blue circles), where λ represents the corrected geomagnetic latitude used by Mayaud (1980). Finally, by inserting δ_{th} into the Eq. (1) we estimated the $L9(\delta_{th})$ level at the observatories of DUR, LMP and NGK.

All these results are reported in Tab.2, which also shows for a comparison, L9 obtained by computing $\delta_a=69^\circ-\lambda$, and $L9_{exp}$ experimentally derived by our calibration procedure ($L9_{exp}$), together with the 95% confidence intervals for the fitted L9 values.

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It can be seen that all $L9_{exp}$ are consistent to each other within their respective confidence interval, at a given observatory. The small difference between $L9_{exp}$ and $L9_{th}$ could be due to a different method for calculating the geomagnetic coordinates used in Mayaud and in this work (we use AACGM). In order to verify this hypothesis, we performed a correction on the key parameter $\delta(\lambda)$ as follows:

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we computed the AACGM latitudes A of geomagnetic observatories from Tab. 5 of Mayaud and corrected λ through linear relationship $\lambda_c = lA + m$;

we performed a linear fit of $\delta(\lambda)$, λ_c , which provides the relationship for the adjusted $\delta_a(\lambda_c)$;

240 finally we performed a linear fit of $L9(\delta)$, δ_A which provides the adjusted $L9_A(A)$ estimated at our geomagnetic observatories as a function of AACGM latitude.

With respect to the $L9(\delta)$ it can be seen that the adjusted $L9_A(A)$ (shown in Tab.2) are closer to the experimental $L9_{exp}$, indicating that the correction on geomagnetic coordinate makes a significant contribution on the $L9$ estimation. LMP is the only one that shows a discrepancy between $L9_{exp}$ and $L9$ here estimated with different methods. A possible reason of this discrepancy lies in the low latitude of LMP observatory where the ring current and/or electrojet currents dynamics could
245 affect $L9$ estimations.

4 Discussion and Conclusions

Four different automated methods for calculation of local geomagnetic activity indices K were endorsed by IAGA, through the ISGI international service, and distributed from ISGI (<http://isgi.unistra.fr/software.php>) web site. For the Italian
250 geomagnetic observatories of Durnia (DUR) and Lampedusa (LMP) we used one of them, i.e. the KASM algorithm that is based on adaptive smoothed method (Nowozyński et al., 1991) which is the only one provided also by INTERMAGNET (<https://www.intermagnet.org/publication-software/software-eng.php>)

An input parameter required by KASM code, as well as FMI code, is the $L9$ value, the so-called "K=9 lower limit", which allows to determine, for each magnetic observatory, the conversion table between classes of geomagnetic field variation
255 ranges and K index values.

We found $L9$ values for DUR and LMP through a correlation analysis using as reference the corresponding data from the two European observatories of Wingst (WNG) and Niemegk (NGK), both located in Germany. The choice of these two observatories was prompted by the fact that they are among the 13 observatories which provide their K indices for the determination of the planetary K_p index and moreover, their magnetic local time is very close to that of the Italian
260 observatories.

We note that NGK is the best reference observatory for Italian geomagnetic observatory of DUR, possibly due to the closest magnetic local time; indeed the amplitude of magnetic disturbances has dependence on (magnetic) local time which inevitably reflects on different K index values (Chambodut et al. (2013)).

Based on a dataset related to a couple of years (2017 and 2018), this analysis allowed to establish that for DUR and LMP the
265 $L9$ values are 320 nT and 310 nT, respectively. These values are in good agreement with the ones directly obtained from Mayaud's method which leads to approximately 355 nT and 315 nT for DUR and LMP, respectively (personal communication, by ISGI members). The method can be generalized and applied to every observatory in the world to verify if the choice to scale local fluctuations of the Earth's magnetic field is properly calibrated by a suitably selected $L9$ value,

regardless if manually or automatically computed. Our analysis also highlighted the possibility of establishing a linear
270 relationship between a pair of analyzed observatory datasets that can be useful for predicting or deriving the index of one
when the other is known.

Another interesting result that we found is related to the consistency of the KASM code and the FMI code, the latter in use at
the two German observatories for the K index computation and subsequent release. Although FMI code is based on a
different procedure, we verified that the results obtained are consistent with those obtained by KASM code and stable in the
275 two-year time interval, although with a slightly different value of the input L9 parameter. This confirms that the choice of a
certain algorithm in place of another does not invalidate the results.

Before the introduction of automatic procedures, based on the definition introduced by Bartels et al. (1939) for the K index
concept, in the '80s of the last century Mayaud (1980) used an empirical relation to calculate the level of the local magnetic
activity L (equivalent to the L9 values) for a generic point of observation with respect to a referenced observatory. Through a
280 linearization process, we used this relation, which includes some approximations and the necessity of determining the
minimum angular separation between the observational point and the auroral region, i.e. a method for determining the
geomagnetic latitude, obtaining an independent estimate of the L9 values for our observatories which is consistent, within
the 95% interval of confidence, with that obtained by our previous analysis. Moreover, Mayaud (1980) notes that the
limitation of the method he proposes is that it is conceived for sub-auroral and mid latitudes; indeed, he suggests that for
285 lower latitudes a constant $L9=300$ nT can be chosen. This very approximate value is not very far from the values we estimate
(320 nT for DUR and 310 nT for LMP), but would certainly be not accurate as them in the comparison with the values from
other reference observatories: indeed our results clearly show that a very precise L9 limit is necessary for obtaining K values
well consistent at different sites. As a final remark, from the overall view of this work, we are also convinced that the habit
to round the value of L9 in multiples of 50 nT, firstly suggested by Bartels et al. (1939) cannot be changed for observatories
290 which have been providing the K index in the past since homogeneity of the series is of primary importance. However,
before a new observatory starts providing K index values, it is worth evaluating K indices with a provisional L9 value,
assigned by ISGI, and then refine with a procedure like the one we have shown, based on the comparison with reference,
well set, observatories.

295 **Author contribution**

DDM, SL and MR planned the study. MR performed the data analysis and wrote the codes. PB studied the KASM code
functionality and, together with MR, tested and validated its results. DDM, LC and SL improved the quality of the
manuscript. All authors read and approved the final manuscript.

300 **Competing interests**

The authors declare that they have no competing interests.

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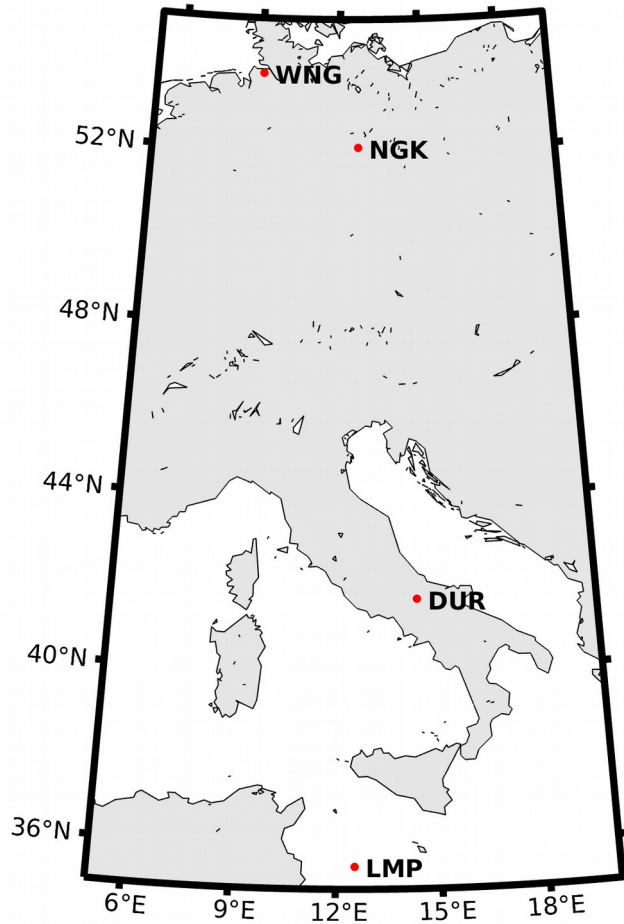
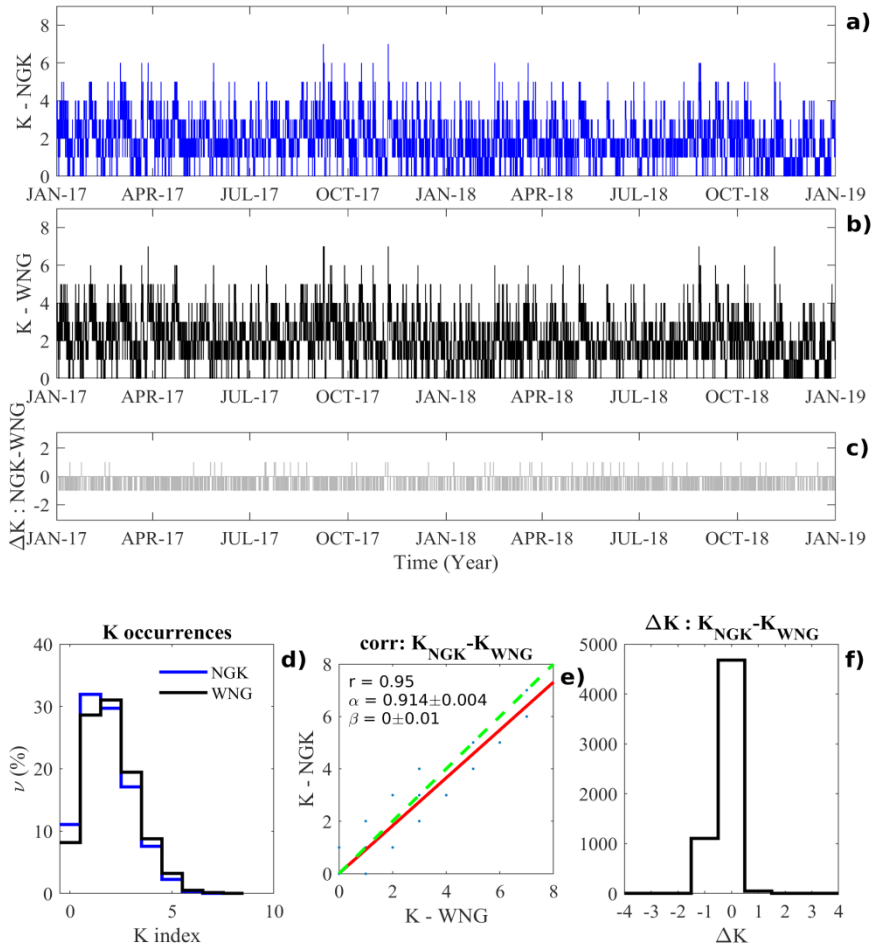


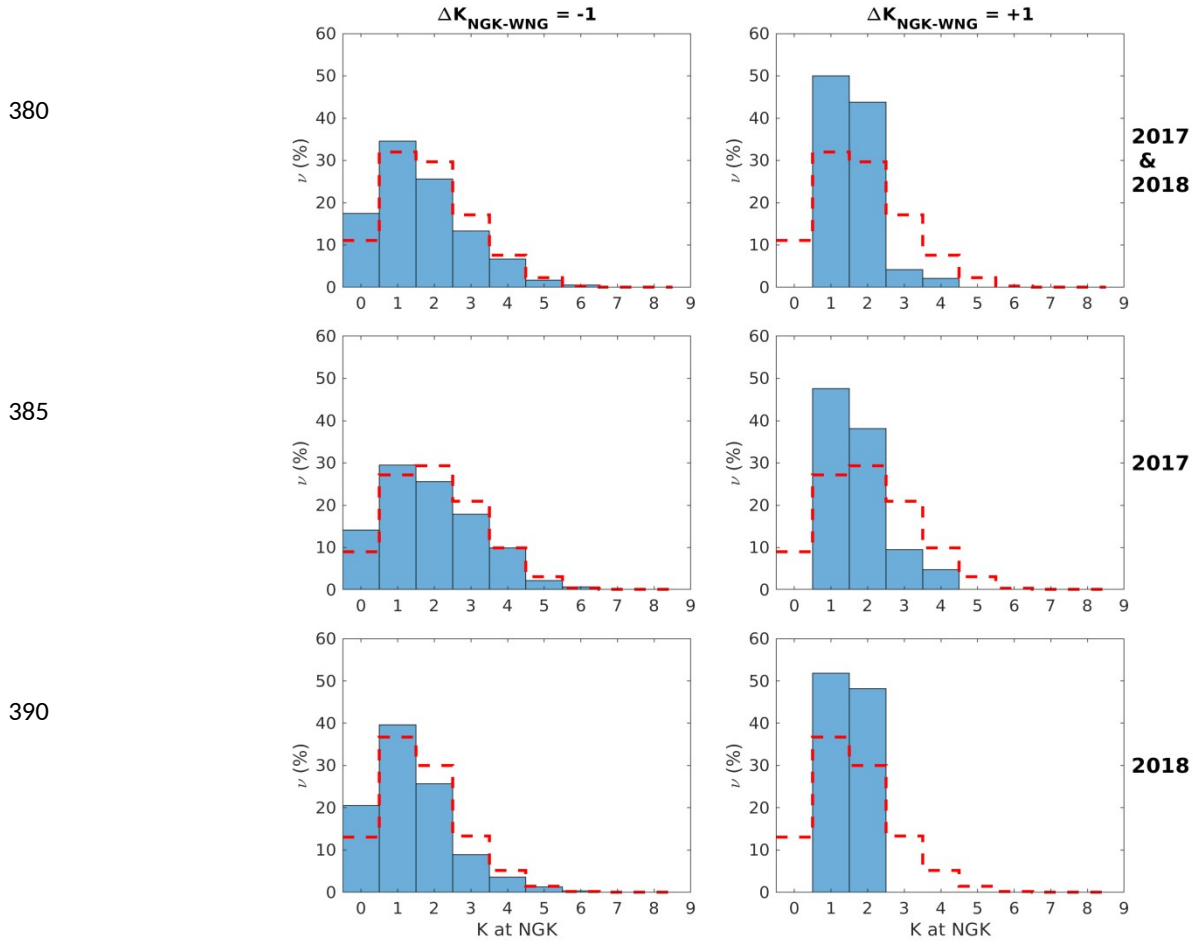
Figure 1: European geomagnetic observatories used in this work



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Figure 2. (top panels) K indices at NGK (panel a) and WNG (panel b) and $\Delta K = K_{NGK} - K_{WNG}$ (panel c). Occurrences of K indices at both observatories (panel d). Linear regression analysis of $K_{NGK} = \alpha K_{WNG} + \beta$ law (red line), by assuming $\beta = 0$, and correlation coefficient r , together with $K_{NGK} = K_{WNG}$ condition (green line). Panel f shows the ΔK distribution.

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395 **Figure 3.** Frequency distributions of K index at NGK (red dashed line) superimposed on both distributions of $K_{NGK} - K_{WNG} = -1$ (left side) and $K_{NGK} - K_{WNG} = 1$ (right side) for analyzed years together (top panels) and separately for each year (middle and bottom panels).

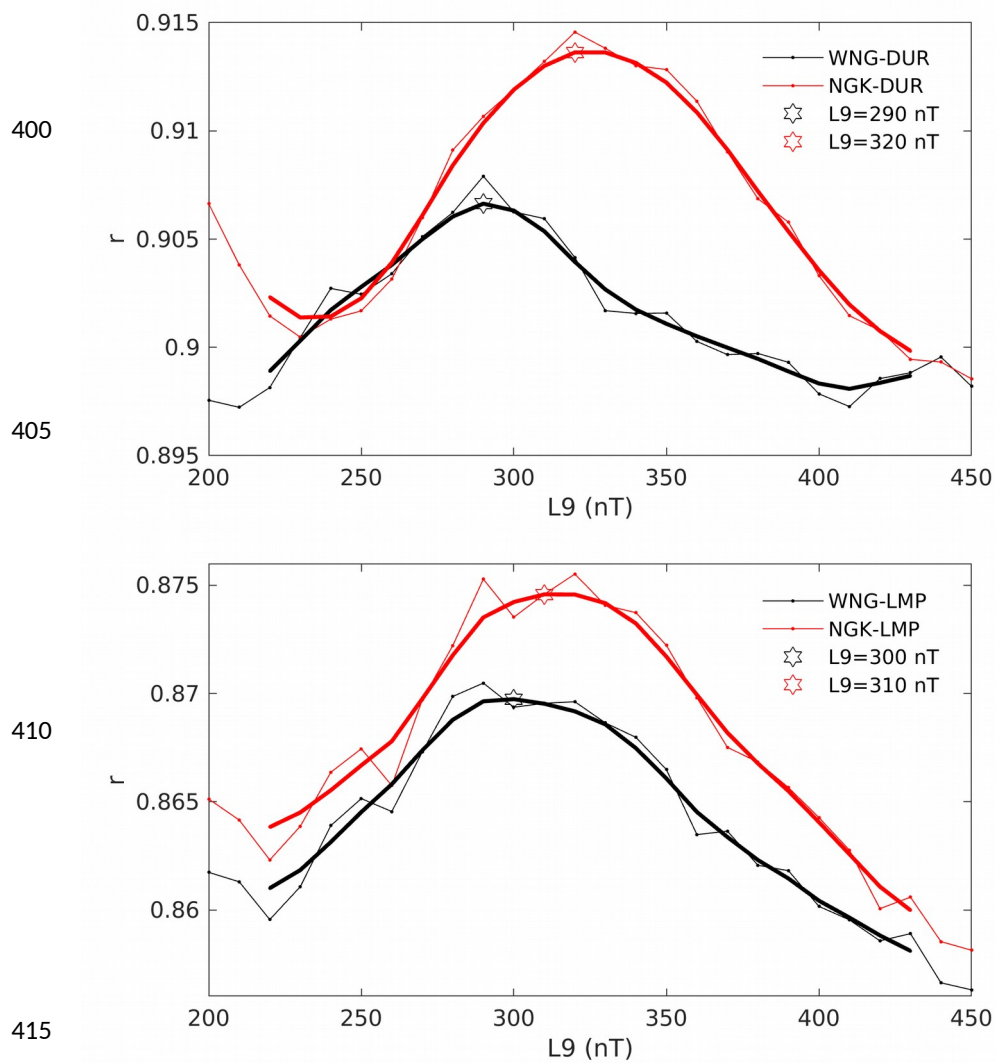
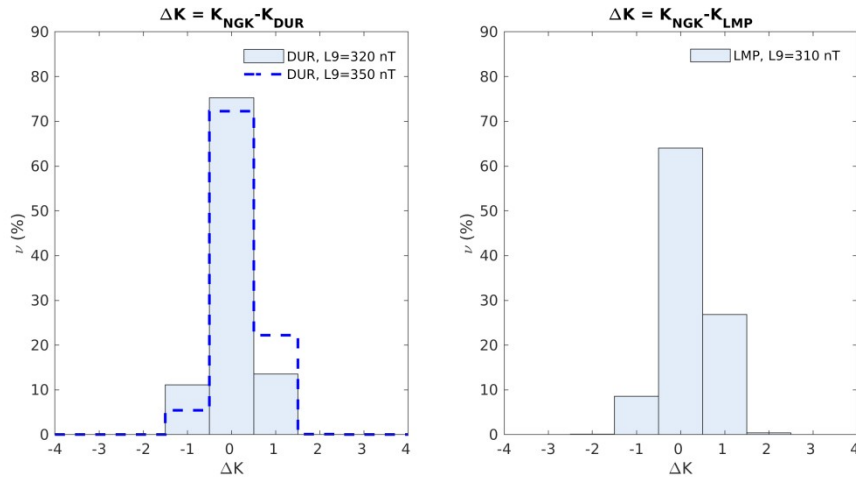


Figure 4. Correlation analyses between K index at NGK and that computed at DUR (top panel) and LMP (bottom panel) by KASM for different L9 values for the 2017-2018 dataset. The thick lines are obtained by smoothing the experimental (thin) lines. In each panel the maximum correlations, referring to the thick lines, are marked by stars (see text for details).

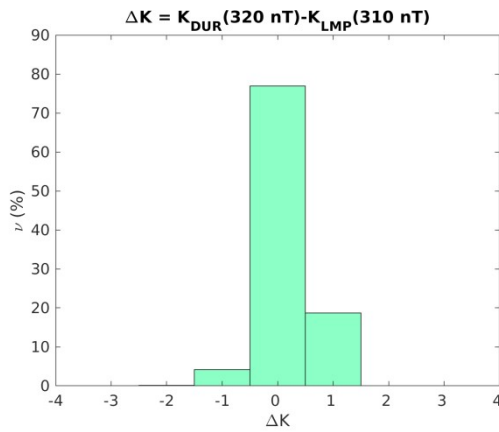
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Figure 5. (left) Frequency distributions of $\Delta K = K_{\text{NGK}} - K_{\text{DUR}}$ for L9=320 nT and, for a comparison, the frequency distribution of $\Delta K = K_{\text{NGK}} - K_{\text{DUR}}$ for L9=350 nT. (right) $\Delta K = K_{\text{NGK}} - K_{\text{LMP}}$ (L9=310 nT).

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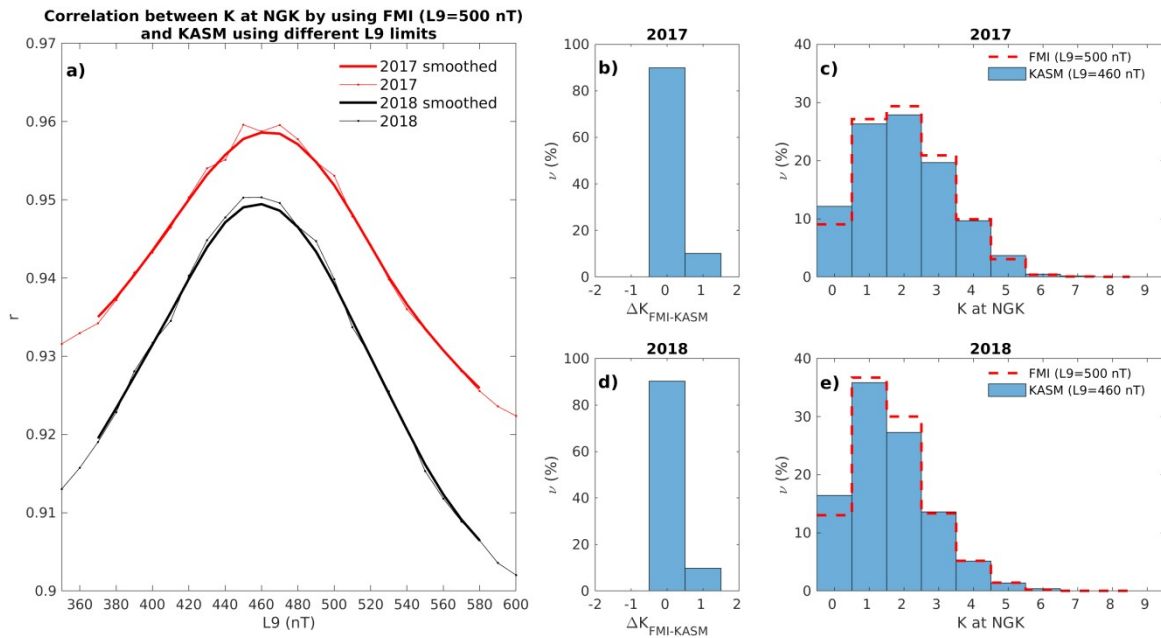
Figure 6. Frequency distribution of $\Delta K = K_{\text{DUR}} - K_{\text{LMP}}$, where K indices are computed by KASM by using L9=320 nT and L9=310 nT for DUR and LMP, respectively.

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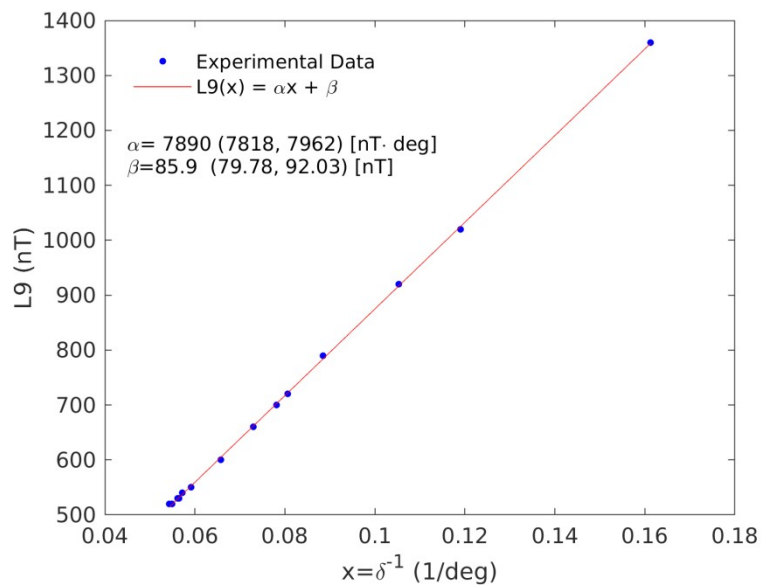


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Figure 7. The FMI and KASM consistency test. (panel a) Correlation analyses between K index at NGK from FMI with L9=500 nT, and that from KASM for different L9 levels, for the years 2017 (definitive NGK 1 min data, red) and 2018 (quasi-definitive NGK 1 min data, black), respectively. The thick lines are obtained by smoothing the experimental (thin) lines. In each year the maximum correlations if found at L9=460 nT. The occurrences of $\Delta K = K_{FMI} - K_{KASM}$ during 2017 (b) and 2018 (d). Frequency distributions of K_{KASM} (460 nT) and K_{FMI} (500 nT) indices for the years 2017 (c) and 2018 (e).

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480 **Figure 8.** The linear relation between L9 limit and $x=1/\delta$ (Eq. 1), where the values are from Mayaud (1980). The linear regression fit results are shown: α and β coefficients and their 95% confidence intervals.

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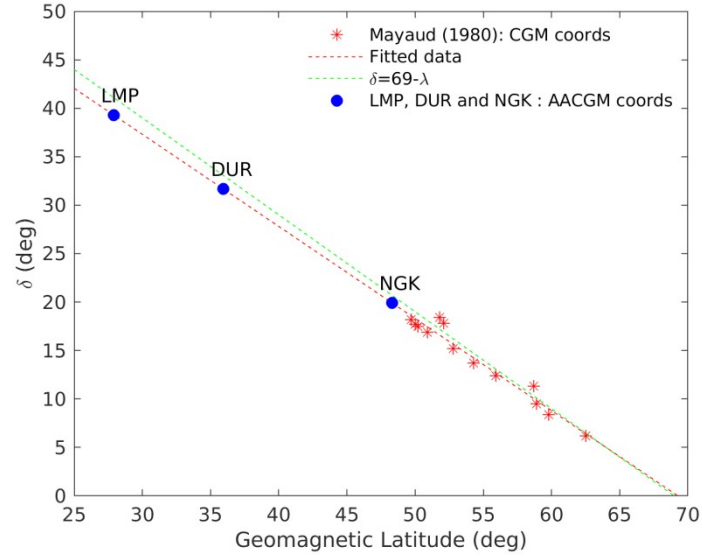


Figure 9. The linear relation between δ and the corrected geomagnetic latitude λ (Eq. 2), where the values from Mayaud (1980) are indicated by red stars and the extrapolated values for our observatories by pink dots. The linear regression fit is shown in red and the relation $\delta = 69^\circ - \lambda$ is shown in green. The blue dots indicate the LMP, DUR and NGK with AACGM latitudes and extrapolated δ_{th} (see text for details).

500 **Table 1.** Geomagnetic observatories used in this study; geographic coordinates; Altitude Adjusted Corrected Geomagnetic Coordinates (AACGM), estimated by using Shepherd (2014) algorithm at 100 km above the observatory and magnetic local time at 0 UT.

Name	CODE	Geographic coordinates	AACGM coordinates	MLT (0 UT)
Lampedusa	LMP	35.52° N, 12.55° E	27.9° N, 86.0° E	00:29
Duronia	DUR	41.65° N, 14.47° E	35.9° N, 88.5° E	00:39
Niemegk	NGK	52.07° N, 12.68° E	48.3° N, 88.9° E	00:40
Wingst	WNG	53.74° N, 9.07° E	50.2° N, 86.2° E	00:30

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Table 2. L9 estimated by different procedures. $\delta_a=69^\circ-\lambda$ (approximate angular distance from auroral region); $L9(\delta_a)$ obtained from δ_a using linear fit in Fig.8; δ_{th} (δ estimated from AACGM lat and the linear fit in Fig. 9); $L9(\delta_{th})$ obtained from δ_{th} using linear fit in Fig.8; $L9_A(A)$ obtained from correction procedure on the key parameter $\delta(\lambda)$ explained at the end of section 3.2. The 95% confidence intervals are also indicated.

Name	δ_a [deg]	$L9(\delta_a)$ [nT] (Conf. Interv.)	δ_{th} [deg]	$L9(\delta_{th})$ [nT] (Conf. Interv.)	$L9_A(A)$ [nT] (Conf. Interv.)	$L9_{exp}$ [nT]
LMP	41	278 (269, 287)	39 (35,43)	288 (268, 313)	270 (248, 294)	310
DUR	33	325 (315, 334)	31 (28, 35)	337 (312, 367)	320 (295, 350)	320
NGK	21	467 (459, 476)	20 (18,22)	482 (441, 535)	475 (432, 529)	460

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