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Space environment (natural and artificial) — Methods for estimation of future geomagnetic activity

Environnement spatial (naturel et artificiel) — Méthodes d'estimation de l'activité magnétique future

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

This second edition cancels and replaces the first edition (ISO 16698:2013), which has been technically revised. The main changes compared to the previous edition are as follows:

— addition of 5.9 and 5.10;

— update of reference lists of Clause 6.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

This document provides guidelines for specifying the process of estimating future geomagnetic activity. Geomagnetic indices describe the variation of the geomagnetic field over a certain time period and provide a measure of the disturbance of the magnetosphere. These indices can be used to estimate upper atmospheric and plasmaspheric densities and many other space environment models. They are also used as the input parameters for orbital lifetime prediction and worst-case environment analysis of electrostatic charging.

The accuracy and method of predicting geomagnetic indices depends on the time scale of prediction. This document presents existing works based on three categories of time scale:

a) short-term prediction (1 h to a few days);

b) middle-term prediction (a few weeks to a few months);

c) long-term prediction (half a year to one solar cycle).

These are required as input parameters for the magnetospheric magnetic field (ISO 22009), upper atmosphere (ISO 14222), ionosphere, plasmasphere (ISO 16457), magnetosphere charged particles and other models of the near-Earth space environment. They also serve as the input parameters for orbital lifetime prediction and worst-case environment analysis of electrostatic charging.

Three International Standards deal with the Earth's magnetic field, including ISO 16695 on the internal magnetic field, ISO 22009 on the magnetospheric magnetic field and this document.

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Space environment (natural and artificial) — Methods for estimation of future geomagnetic activity

1 Scope

This document specifies the methods used for estimating geomagnetic indices for time intervals ranging from short-term (hours to a few months) to long-term (months to years). This document is intended for use to predict future geomagnetic indices and space environment.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Symbols and abbreviated terms

Bs	Southward component of the interplanetary field ($Bs = 0$ when $Bz \geq 0$ and $Bs = Bz$ when $Bz < 0$)
Bz	North-south component of the interplanetary field
F10.7 flux	Measure of the solar radio flux at a wavelength of 10,7 cm at the earth's orbit, given in units of 10^{-22} W·m^{-2}
GLat	Geographic latitude
GLon	Geographic longitude
IMF	Interplanetary magnetic field
MLat	Geomagnetic latitude
MLon	Geomagnetic longitude
MHD	Magnetohydrodynamics
Sq	Daily geomagnetic field variations during quiet conditions (Solar quiet)
UT	Universal time

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5 General parameters

5.1 Geomagnetic field variations

The geomagnetic field consists of internal and external magnetic fields. The internal (main) magnetic field is produced by source currents that are mostly inside the Earth's core and by induced currents present in the solid Earth and the ocean, caused by the temporal variation of external magnetic fields. The external magnetic field is produced by magnetospheric and ionospheric currents.

The magnetosphere is highly dynamic with time scales ranging from minutes to days. Solar wind is the ultimate source of magnetospheric dynamics. The role played by the IMF north-south component, Bz, is particularly important and its southward component, Bs, plays a fundamental role in substorm and magnetic storm activity through the process of magnetic field line reconnection. Solar wind speed also plays an essential role in these dynamics.

5.2 Quiet level and disturbance fields

Five days of every month are selected as the Five International Quietest Days using the Kp index (see 5.4.2). Note that the five quietest days are selected regardless of the absolute level of quietness. Thus, in a disturbed month, the quietest days may not be very quiet.

Derivation: The quietest days (Q-days) of each month are selected using the Kp indices based on three criteria for each day: (1) the sum of the eight Kp values, (2) the sum of squares of the eight Kp values and (3) the maximum of the eight Kp values. According to each of these criteria, a relative order number is assigned to each day of the month; the three order numbers are then averaged and the days with the first to fifth lowest mean order numbers are selected as the five international quietest days.

Reference: Website of the Deutsches GeoForschungsZentrum (http://www-app3.gfz-potsdam.de/kp_index/qddescription.html).

Once the quiet level is determined using the Five International Quietest Days, disturbance fields can be obtained as deviations from the quiet level of geomagnetic field.

5.3 K index (local 3 h range index)

The K index is a number in the range of 0 (quiet) to 9 (disturbed) that provides a local classification of the variations of the geomagnetic field observed after subtraction of the regular daily variation (Sq). Each activity level relates almost logarithmically to the corresponding disturbance amplitude of the horizontal field component during a 3 h UT interval. In a day, eight K indices are given in successive 3 h UT (universal time) intervals (0 h to 3 h, 3 h to 6 h, ..., 21 h to 24 h UT).

Derivation: The ranges R for the H and D (or X and Y) components are defined as the expected difference between the highest and lowest deviation, within the three-hour interval, from a smooth curve (a regular daily variation) for that element on a magnetically quiet day. Only the larger value of R, i.e. R for the most disturbed element, is taken as the basis of K. To convert from R to K, a permanent scale prepared for each observatory is used. Table 1 is an example of the permanent scale for the Niemegk observatory.

References: Bartels, et al. [1939][11], Mayaud [1980][37], Menvielle, et al. [2011][42].

Table 1 — Permanent conversion scale from R to K for Niemegk observatory

Range (nT)	0–5	5–10	10–20	20–40	40–70	70–120	120–200	200–330	330–500	≥500
K value	0	1	2	3	4	5	6	7	8	9

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5.4 Kp, ΣKp, ap and Ap indices (planetary indices)

5.4.1 General

The planetary indices, Kp, ΣKp, ap and Ap, are derived from 13 selected mid-latitude observatories (see Table 2). The derivation scheme for each index is described in the corresponding subsection.

Table 2 — Thirteen observatories that contributed to the Kp index

Observatory, country	Code	GLat (°N)	GLon (°E)	MLat (°)	Notes
Meannook, Canada	MEA	54,617	246,667	62,5	
Sitka, USA	SIT	57,058	224,675	60,0	
Lerwick, Shetland Is.,UK	LER	60,133	358,817	58,9	
Ottawa, Canada	OTT	45,400	284,450	58,9	Replaced Agincourt in 1969
Uppsala, Sweden	UPS	59,903	17,353	58,5	Replaced Lovo in 2004
Eskdalemuir, UK	ESK	55,317	356,800	54,3	
Brorfelde, Denmark	BJE	55,625	11,672	52,7	Replaced Rude Skov in 1984
Fredericksburg, USA	FRD	38,205	282,627	51,8	Replaced Cheltenham in 1957
Wingst, Germany	WNG	53,743	9,073	50,9	
Niemegk, Germany	NGK	52,072	12,675	48,8	Replaced Witteveen in 1988
Hartland, UK	HAD	50,995	355,517	50,0	Replaced Abinger in 1957
Canberra, Australia	CNB	−35,317	149,367	−45,2	Replaced Toolangi in 1981
Eyrewell, New Zealand	EYR	−43,424	172,354	−50,2	Replaced Amberley in 1978

5.4.2 Kp index (planetary 3 h range index)

The Kp index is assigned to successive 3 h UT intervals (0 h to 3 h, 3 h to 6 h, ..., 21 h to 24 h UT), giving eight values per UT day and ranges in 28 steps from 0 (quiet) to 9 (disturbed) with intermediate values denoted by −, o, or +, resulting in 0o, 0+, 1−,1o, 1+, 2−, 2o, 2+, ..., 8−, 8o, 8+, 9− and 9o.

Derivation: The K indices at the 13 observatories given in Table 2 are standardized by means of conversion tables that have been established through the rather complicated procedure introduced by Bartels [1949][10]. The standardized K indices, called the Ks index, are averaged using weighting factors to derive the Kp index.

References: Bartels [1949][10], Mayaud [1980][37], Menvielle, et al. [2011][42].

5.4.3 ΣKp index (planetary daily range index)

ΣKp is the sum of the eight Kp values of the day.

5.4.4 ap index (planetary 3 h equivalent amplitude index)

The Kp index is not linearly related to the geomagnetic disturbances measured in the unit of nT. Instead, the ap index is introduced as it is roughly proportional to the geomagnetic disturbances. One ap unit corresponds to approximately 2 nT of geomagnetic variations.

Derivation: The ap index is derived directly from the Kp index by using the conversion table shown in Table 3.

References: Bartels and Veldkamp [1954][12], Mayaud [1980][37], Menvielle, et al. [2011][42].

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Table 3 — Conversion table from the Kp index to the ap index

Kp	0o	0+	1−	1o	1+	2−	2o	2+	3−	3o	3+	4−	4o	4+
ap	0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp	5−	5o	5+	6−	6o	6+	7−	7o	7+	8−	8o	8+	9−	9o
ap	39	48	56	67	80	94	111	132	154	179	207	236	300	400

5.4.5 Ap index (planetary daily equivalent amplitude index)

The Ap index is the average of the eight values of the ap index in a UT day.

5.5 aa index (antipodal amplitude index)

The aa index is a simple measure of global geomagnetic activity, which can be traced back continuously to 1868.

Derivation: The aa index is produced from the K indices of two nearly antipodal magnetic observatories in England and Australia, which are listed in Table 4. The K indices at the two observatories are converted back to amplitudes using Table 5. The aa index is computed as an average of the northern and southern values of amplitude using the weighting factors, λ, shown in Table 4.

References: Mayaud [1971][36].

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Table 4 — Observatories in England and Australia contributing to the aa index

Observatory, country	Code	Period	GLat (°N)	GLon (°E)	MLat (°)	λ
Greenwich, England		1868–1925				1,007
Ablinger, England	ABN	1926–1956	51,18	359,62	53,4	0,934
Hartland, England	HAD	1957–	50,97	355,52	54,0	1,059
Melbourne, Australia		1868–1919				0,967
Toolangi, Australia	TOO	1920–1979	−37,53	145,47	−45,6	1,033
Canberra, Australia	CNB	1979–	−35,30	149,00	−42,9	1,084

Table 5 — Conversion table from the K index at the aa observatories to amplitudes

K index	0	1	2	3	4	5	6	7	8	9
Amplitude	2,3	7,3	15	30	55	95	160	265	415	667

5.6 Dst index (storm time disturbance index)

The Dst index is a measure of the axially symmetric part of the H component along the geomagnetic equator on the ground and the main physical source is a combination of the equatorial ring current, the plasma sheet current and the magnetopause current.

Derivation: The Dst index is defined as the average of the disturbance variations of the H component, D_i, at the four observatories (i = 1 to 4) listed in Table 6, divided by the average of the cosines of the dipole latitudes at the observatories for normalization to the dipole equator. Dst is computed for each UT hourly interval from the four observatories.

References: Sugiura [1964][54], Sugiura and Kamei [1991][55].

Table 6 — Four observatories contributing to the Dst index

Observatory, country	Code	GLat (°N)	GLon (°E)	Dipole Lat (°)
Kakioka, Japan	KAK	36,230	140,190	26,0

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Table 6 *(continued)*

Observatory, country	Code	GLat (°N)	GLon (°E)	Dipole Lat (°)
San Juan, USA	SJG	18,113	293,850	29,6
Honolulu, USA	HON	21,320	201,998	21,1
Hermanus, South Africa	HER	−34,425	19,225	−33,3

5.7 ASY and SYM indices (mid-latitude disturbance indices)

The disturbance fields in mid- and low latitudes are generally not axially symmetric, in particular in the developing phase of a magnetic storm. To describe the asymmetric and symmetric disturbance fields in mid-latitudes with a high time resolution of 1 min, longitudinally asymmetric (ASY) and symmetric (SYM) disturbance indices were introduced and derived for both the H and D components. The SYM-H index is approximately the same as the Dst index, while its time resolution is 1 min.

Derivation: The ASY/SYM indices are derived from six selected mid-latitude observatories (see Table 7) in the following four steps: (1) subtraction of the geomagnetic main field and the Sq field to obtain the disturbance field component, (2) coordinate transformation to a dipole coordinate system by using a rotation angle that is an angle between the geomagnetic dipole pole position and local geomagnetic direction, (3) calculation of the longitudinally symmetric indices, SYM-H and SYM-D, by taking averages of disturbance fields of the six stations and (4) calculation of the asymmetric disturbance indices, ASY-H and ASY-D, by computing the range between the maximum and the minimum asymmetric fields.

References: Iyemori, et al. [1992][26], Menvielle, et al. [2011][42].

Table 7 — Six observatories contributing to the SYM/ASY indices

Observatory, country	Code	GLat (°N)	GLon (°E)	MLat (°)	MLon (°E)	Rotation angle (°)
Memambetsu, Japan	MMB	43,9	144,2	34,6	210,2	−16,0
Honolulu, USA	HON	21,3	202,0	21,5	268,6	−0,6
Tuscon, USA	TUC	32,3	249,2	40,4	314,6	2,02
Fredericksburg, USA	FRD	38,2	282,6	49,1	352,2	11,8
Hermanus, South Africa	HER	−34,4	19,2	−33,7	82,7	−12,7
Alma Ata	AAA	43,3	76,9	34,5	153,0	11,0

5.8 AU, AL, AE and AO indices (auroral electrojet indices)

The auroral electrojet indices are measures of the intensity of the auroral electrojets and consist of four indices, AU, AL, AE and AO. The AU and AL indices are intended to express the strongest current intensity of the eastward and westward auroral electrojets, respectively. The AE index represents the overall activity of the electrojets and the AO index provides a measure of the equivalent zonal current.

Derivation: The auroral electrojet indices are derived from geomagnetic variations in the H component observed at 12 selected observatories along the auroral zone in the northern hemisphere (see Table 8). The AU and AL indices are respectively defined by the largest and the smallest values thus selected. The symbols, AU and AL, derive from the fact that these values form the upper and lower envelopes of the superposed plots of all the data from these stations as functions of UT. The difference, AU minus AL, defines the AE index and the mean value of the AU and AL, i.e. (AU+AL)/2, defines the AO index.

References: Davis and Sugiura [1966][42], Kamei and Maeda [1981][30].

Table 8 — Twelve (and obsolete three) observatories contributing to the AE index

Observatory, country	Code	GLat (°N)	GLon (°E)	MLat (°)	MLon (°E)	Notes
Abisko, Sweden	ABK	68,36	18,82	66,06	114,66	
Dixon Island, Russia	DIK	73,55	80,57	64,04	162,53	

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Table 8 *(continued)*

Observatory, country	Code	GLat (°N)	GLon (°E)	MLat (°)	MLon (°E)	Notes
Cape Chelyuskin, Russia	CCS	77,72	104,28	67,48	177,82	
Tixie Bay, Russia	TIK	71,58	129,00	61,76	193,71	
Pebek, Russia	PBK	70,09	170,93	63,82	223,31	Opened in 2001/04
Barrow, USA	BRW	71,30	203,25	69,57	246,18	
College, USA	CMO	64,87	212,17	65,38	261,18	
Yellowknife, Canada	YKC	62,40	245,60	68,87	299,53	
Fort Churchill, Canada	FCC	58,80	265,90	67,98	328,36	
Sanikiluaq, Canada	SNK	56,5	280,8	66,6	349,7	Opened in 2007/12
Narssarssuaq, Denmark	NAQ	61,20	314,16	69,96	37,95	
Leirvogur, Iceland	LRV	64,18	338,30	69,32	71,04	
Cape Wellen, Russia	CWE	66,17	190,17	62,88	241,36	Closed in 1996
Great Whale River, Russia	GWR	55,27	282,22	65,45	351,77	Closed in 1984/07
Poste-de-la-Baleine, Canada	PBQ	55,27	282,22	65,45	351,77	Opened in 1984/09 Closed in 2007/11

5.9 am index

The am index is designed to measure global geomagnetic activity using a large set of stations representing all longitudes and possible hemispheric discrepancies. Time resolution of the am index is 3 h (0 h to 3 h, 3 h to 6 h, ..., 21 h to 24 h UT), giving eight values per UT day, same as the Kp index. However, the index is given in the unit of nT.

Derivation: Stations to derive the am index are divided into groups according to their longitude (Table 9), with five longitude sectors in the northern hemisphere and four in the southern hemisphere (there were only three before 1979). In each longitude sector, the K values are averaged and the result is converted into amplitude using mid-class amplitudes for L9 = 500 nT (L9 being the K=9 lower limit; conversion table is given by Mayaud, P. N. [1980][37]). The amplitude is multiplied by a weighting factor to balance the different ranges in longitude of the different sectors and then averaged to give the hemispheric indices an (North) and as (South). The planetary index am is equal to (an + as)/2.

References: Mayaud [1968, 1980][35], [37].

Table 9 — Observatories that contributed to the am index

Longitudinal group	Observatory, country	Code	Period	GLat (°N)	GLon (°E)	MLat (°)
(G1)	Magadan, Russia	MGD	1967–	60,12	151,02	52,01
	Petropavlovsk, Russia	PET	1969–	53,10	158,63	45,95
	Memambetsu, Japan	MMB	1959–	43,91	144,19	35,35
(G2)	Arti (Sverdlovsk), Russia	ARS	1959–	56,43	58,57	49,13
	Novosibirsk, Russia	NVS	2002–	55,03	82,90	44,92
	Podkammenaya T. Russia	POD	1973–2001	61,40	90,00	51,54
	Tomsk, Russia	TMK	1959–1970	56,47	84,93	46,88
(G3)	Hartland, UK	HAD	1959–	51,00	355,52	53,9
	Niemegk, Germany	NGK	1959–	52,07	12,68	51,88
	Chambon-la-Forêt, France	CLF	1996–	48,03	2,26	49,84
	Witteveen, Netherland	WIT	1959–1988	52,81	6,67	53,66
(G4)	Ottawa, Canada	OTT	1975–	45,40	284,45	55,63

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Table 9 *(continued)*

Longitudinal group	Observatory, country	Code	Period	GLat (°N)	GLon (°E)	MLat (°)
	Fredericksburg, USA	FRD	1959–	38,20	282,63	48,4
(G5)	Newport, USA	NEW	1975–	48,27	242,88	54,85
	Victoria, Canada	VIC	1959–	48,52	236,58	54,14
	Tucson, USA	TUC	1959–	32,17	249,27	39,88
(G6)	Canberra, Australia	CNB	1986–	−35,32	149,36	−42,71
	Eyrewell, New Zealand	EYR	1978–	−43,41	172,35	−47,11
	Amberley, New Zealand	AML	1959–1977	−43,15	172,72	−46,80
	Lauder, New Zealand	LDR	1979–1985	−43,03	169,41	−49,18
(G7)	Gnangara, Australia	GNA	1959–	−31,78	115,95	−41,93
	Martin de Vivies France	AMS	1986–	−37,80	77,57	−46,39
	Toolangi, Australia	TOO	1959–1984	−37,53	145,47	−45,38
	Canberra, Australia	CNB	1979–1985	−35,32	149,36	−42,71
(G8)	Kerguelen Is., France	PAF	1959–	−49,35	70,26	−56,94
	Crozet Is., France	CZT	1973–	−46,43	51,86	−51,35
	Hermanus, South Africa	HER	1959–	−34,43	19,23	−33,98
(G9)	Argentine Is., Ukraine	AIA	1959–	−65,25	295,73	−55,06
	Trelew, Argentina	TRW	1973–	−43,25	294,69	−33,05
	South Georgia, UK	SGG	1975–1982	−54,28	323,52	−45,57

5.10 PC index

The PC index intends to monitor the geomagnetic activity over the polar caps caused by changes in the IMF and solar wind, driven by the geoeffective interplanetary electric field. A single station near the northern or southern pole (Table 10) is used to derive the PCN (northern) or PCS (southern) index. The index is given in the unit of nT with a time resolution of 1 min.

Derivation: The PC index is deduced from the deviations in the horizontal H and D magnetic field components from the quiet level at two polar cap stations. More specific and detailed information may be found in references.

References: Troshichev et al. [1979, 1988, 2006][61], [62], [63].

Table 10 — Observatories that contributed to the PC index

Observatory	Code	GLat (°N)	GLon (°E)	MLat (°)
Thule (Qaanaaq), Greenland	THL	77,483	290,773	87,02
Vostok, Antarctica	VOS	−78,464	106,835	88,07

5.11 Time lag in the derivation and temporal resolution (sampling)

Some of the indices mentioned above have different classes (generations) for operational use. That is, for quasi-real-time derivation, a different naming convention is used to distinguish from the original definition with quality-controlled data. For example, in the case of the Dst index, there are Real-Time (Quick-Look) Dst, Provisional Dst and Final Dst. There are also attempts to increase the temporal resolution of the indices (e.g. Gannon and Love [2011][68]). (See Annex A.)

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6 Classification of prediction

6.1 General

The accuracy and method of predicting geomagnetic indices depends on the time scale of prediction. 6.2 to 6.4 introduce some of the existing works which are based on a classification of three time-scale categories: short-term (1 h to a few days), middle-term (a few weeks to a few months) and long-term (half a year to one solar cycle). Some of them are actually used and the results made available online (see Annex B).

6.2 Short-term prediction

Stimulated by the space weather programmes, there are many proposed methods and related research papers for predicting geomagnetic indices in a time scale of 1 h to a few days. These fall into four categories: (1) linear or non-linear prediction filter, (2) machine learning, (3) probabilistic prediction with solar wind data and (4) physics-based model (MHD simulation etc). Most of the recent techniques need real-time solar wind parameters and near-real-time geomagnetic observations as the input. Predicting solar wind disturbance from solar surface observation may be a key to improving geomagnetic index predictions.

Examples of prediction:

Kp, ap and Ap indices: McPherron [1999][40] (Type 1), Solares, et al. [2016][51] (Type 1), Boberg, et al. [2000][14] (Type 2), Costello [1998][16] (Type 2), Thompson [1996][59] (Type 2), Wing, et al. [2005][65] (Type 2), Detman and Joselyn [1999][21] (Type 2), Bala, et al. [2009][6] (Type 2), Bala and Reiff [2012][7] (Type 2), Tan, et al. [2018][57] (Type 2), Wintoft, et al. [2017][66] (Type 2), McPherron, et al. [2004][69] (Type 3), Savani, et al. [2017][50] (Type 3), Haiducek, et al. [2017][25] (Type 4).

Dst index: Balikhin, et al. [2001][9] (Type 1), Boaghe, et al. [2001][13] (Type 1), Iyemori and Maeda [1980][27] (Type 1), Chandorkar, et al. [2017][18] (Type 1), Gruet, et al. [2018][24] (Type 1), Lundstedt [1996][33] (Type 2), Stepanova, et al. [2005][53] (Type 2), Revallo, et al. [2014][49] (Type 2), Burton, et al. [1975][15] (Type 3), O'Brien and McPherron [2000][45] (Type 3), Temerin and Li [2002][58] (Type 3), Podladchikova and Petrukovich [2012][47] (Type 3), Tobiska, et al. [2013][60] (Type 3), Tsubouchi and Kubo [2010][64] (Type 3), Fok, et al. [2001][23] (Type 4), Jordanova, et al. [2010][28] (Type 4).

AE indices: Iyemori and Maeda [1980][27] (Type 1), Li, et al. [2007][32] (Type 1), Luo, et al. [2013][34] (Type 1), Pallocchia, et al. [2008][46] (Type 2), Takalo and Timonen [1999][56] (Type 2), Amariutei and Ganushkina [2012][5] (Type 2), Li, et al. [2007][32] (Type 3), Kitamura, et al. [2008][31] (Type 4), Mays, et al. [2009][38] (Type 4).

6.3 Middle-term prediction

There are only a few research papers that use recurrences of geomagnetic disturbances in a time scale of a few weeks to a few months.

Example of prediction: Zhou and Wei [1998][67] (prediction of the Kp index).

6.4 Long-term prediction

There are very few proposed techniques and/or research papers on predicting geomagnetic indices in a time scale of half a year to one solar cycle, as compared with those on solar activities such as sun spot numbers or F10.7 flux. However, the sun spot number or F10.7 flux indicates quite different behaviour from geomagnetic indices such as the aa index during some solar cycles. Therefore, the long-term prediction method of geomagnetic indices is necessary.

Examples of prediction: Niehuss, et al. [1996][44] (prediction of the Ap index), Cliver, et al. [1999][20] (prediction of the aa index).

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Long-term prediction of solar activities (sun spot number and F10.7 flux) is presented by NOAA/*Space Weather* Prediction Center (see Annex B). The possibility of combining the technique of solar activity prediction with the solar-geomagnetic disturbance relationship has been examined in a number of studies.

Examples of solar-geomagnetic disturbance relationship: Clilverd, et al. [1998][19], Stamper, et al. [1999][52].

7 Methods of prediction

7.1 General

The prediction methods can be split into two broad categories: (1) those based on a statistical model and (2) those based on a physical principle.

7.2 Prediction based on statistical models

7.2.1 Linear or non-linear prediction filter

This method of prediction uses data from a preceding interval of similar (or longer) length to that of the period to be predicted. Precision of prediction generally depends on the temporal distance between the most recent data and the period to be predicted. There are two types of prediction: one uses the index of the preceding interval as the input data (see Zhou and Wei [1998][67]) and the other uses the solar wind parameters (see Iyemori and Maeda [1980][27]; McPherron, et al. [1986][41]; Li, et al. [2007][32]; Solares, et al. [2016][51]; Chandorkar, et al. [2017][18]; Gruet, et al. [2018][24]; Luo, et al. [2013][34]).

7.2.2 Machine learning

There are several neural-network and deep learning models. This method is applicable for time scales of several days to one sunspot cycle. It has been concluded that the interplanetary magnetic field and solar wind plasma data are significant components for any of the models (see Thomson [1996][59]; Wing, et al. [2005][65]; Tan, et al. [2018][57]; Amariutei and Ganushkina [2012][5]; Bala, et al. [2009][6]; Bala and Reiff [2012][7]; Revallo, et al. [2014][49]; Wintoft, et al. [2017][66]).

7.2.3 Probabilistic prediction

This method is based on the periodicity of geomagnetic disturbances such as the sun spot cycle, annual or semi-annual variation (see Joselyn [1995][29]; Tsubouchi and Kubo [2010][64]; Zang and Moldwin [2015][70]). Predictions made over long time scales (one to ten years) require the prediction of a sunspot number (see Feynman and Gu [1986][71]). Similar techniques used to predict the F10.7 flux and Ap index (e.g. Niehuss, et al. [1996][44]; Tobiska, et al. [2013][60]) are also available.

7.3 Prediction based on physical principle

This type of prediction is based on numerical MHD simulation of the magnetospheric process or energy principle. These methods need the solar wind parameters as the input. See, for example, Burton, et al. [1975][15], Kitamura, et al. [2008][31], Haiducek, et al. [2017][25], Jordanova, et al. [2010][28], Mays, et al. [2009][38].

8 Evaluation of prediction efficiency

8.1 Definition of prediction error

For a simple time series, the most popular definition of prediction error is as the average of the square of the differences between the predicted values and the observed values. This provides a reasonable measure of prediction error.

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8.2 Methods of evaluation

It has been reported that the accuracy of prediction is different for the sunspot maximum and minimum period. It has also been reported that the accuracy is different for different solar cycles (see Feynman and Gu [1986][71]). Accuracy is also different depending on the time scale of prediction. The prediction efficiency shall therefore be given together with the conditions applied for its evaluation.

A prediction can be evaluated using a skill score. In the case of a dichotomous forecast, the true skill statistics, the Gilbert skill score, the Heidke skill score and others can be used (see Detman and Joselyn [1999][21]). If predicting continuous-variables, the mean square skill score can be used (see Murphy [1988][43]). These skill scores are detailed in Annex C.

Rastätter, et al. [2013][48] evaluated the performance of various prediction models against the Dst index, using skill scores.

9 Compliance criteria

9.1 Rationale

The prediction principle and scheme shall be described concisely and clearly. They shall be published as scientific articles in refereed/peer-review international journals and their references shall be available to the public. Otherwise, journal-style documents suitable for publication in international journals shall be accessible to the public.

9.2 Reporting

Prediction results of geomagnetic indices shall be made public for evaluation and application by third parties (e.g. individuals or institutes who are interested in the prediction results). As a minimum, digital values of the prediction results shall be given in the same data format as the corresponding geomagnetic indices, such as the World Data Center exchange format.

9.3 Documenting

The following information relating to prediction shall be clearly documented or displayed.

a) Input:

   1) types of data;

   2) source of data;

   3) time resolution of data;

   4) number of data points;

   5) time of data acquisition.

b) Output:

   1) types of predicting data;

   2) time of predicting data;

   3) time at which prediction was performed.

c) Miscellaneous:

   1) type of prediction method (choose from the four types listed in Clause 4, otherwise describe briefly);

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2) point of contact.

9.4 Publishing

When the geomagnetic index becomes available, comparison shall be made with the prediction results. Comparison includes calculating the prediction error, skill score, correlation coefficients and so on, as listed in Clause 8.

9.5 Archiving

The results of prediction shall be archived and available to the public for evaluation.

10 Useful Informative Documents

Many useful academic documents related with this document's fields have been published. Those are listed in Annex D.

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Annex A
(informative)

Websites where geomagnetic indices are available

(1) GFZ-Potsdam
http://www-app3.gfz-potsdam.de/kp_index/ (Kp)

(2) Service International des Indices Géomagnetiques (ISGI)
http://isgi.unistra.fr/about_indices.php (aa, am, Kp, AE, Dst, PC)

(3) WDC for Geomagnetism, Kyoto
http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html (AE, Dst, ASY/SYM, RT-AE, RT-Dst)

(4) Arctic and Antarctic Research Institute
http://pcindex.org/ (PCS)

(5) WDC for Geomagnetism, Copenhagen
ftp://ftp.space.dtu.dk/WDC/indices/pcn/ (PCN)

(6) US Geological Survey
http://geomag.usgs.gov/dst/ (RT-USGS-Dst)

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Annex B
(informative)

Websites where the space weather predictions and/or "now casting" are presented

(1) NOAA Space Environment Center
http://www.swpc.noaa.gov/

(2) Magnetospheric Specification and Forecast model (MSFM)
http://space.rice.edu/ISTP/dials.html

(3) International Space Weather Service
http://www.ises-spaceweather.org/

(4) NICT Space Environment Information Service
http://hirweb.nict.go.jp/

(5) Belgium SIDC
http://sidc.oma.be/

(6) The Australian Space Weather Agency
http://www.ips.gov.au/Space_Weather

(7) WINDMI model
https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=WINDMI

(8) Lund space weather model
http://www.lund.irf.se/rwc/

(9) CISM forecast model
http://www.bu.edu/cism/ and http://lasp.colorado.edu/cism/

(10) Solar Cycle Progression, NOAA/Space Weather Prediction Center
http://www.swpc.noaa.gov/SolarCycle/

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Annex C
(informative)

Definition of various skill scores

C.1 Dichotomous forecast

Table C.1 shows the contingency table used in the following formula.

Table C.1 — Contingency table comparing forecast and observed results

		Forecast	
		Yes	**No**
Observed	**Yes**	x (hits)	y (misses)
	No	z (false alarm)	w (correct negatives)

The true skill score (T) is defined as:

$$T = \frac{xw - yz}{(x+y)(z+w)}$$

The Gilbert skill score (G) is defined as:

$$G = \frac{x - c_1}{x + y + z - c_1}$$

The Heidke skill score (H) is defined as:

$$H = \frac{x + w - c_2}{x + y + z + w - c_2}$$

C.2 Continuous variables

The mean-square skill score (S) is defined as:

$$S = 1 - \frac{E(f,x)}{E(\bar{x},x)}$$

$$E(f,x) = \frac{1}{n}\sum_{i=1}^{n}(f_i - x_i)^2$$

where

E represents “mean square error”;

f_i is the ith forecast;

x_i is the ith observation;

$\bar{x}$ is the mean value of x over $i = 1 - n$.

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Annex D
(informative)

Useful academic documents related with this document's fields are presented (These are not cited in the document)

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