Ground-based Instrumentation for Space Weather Observations I

Lectures for the ICTP School
Trieste, Italy  October 2010
Peter Stauning, DMI
Agenda (part I):

1. Introduction. The Carrington Storm.

2. Geospace.
   2.1. Earth’s magnetic field
   2.2. Atmosphere and Ionosphere

   3.1. Instrumentations
   3.2. Geospace currents.
   3.3. Magnetic indices.

Links and References
Carrington’s report to The Royal Astronomical Society:

_Carrington’s report to The Royal Astronomical Society:

**Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.**

“While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun’s disk was, as usual with me, projected to a plate of glass coated with distemper. I had secured diagrams of all the groups and detached spots, when within the area of the great north group, two patches of intensely bright and white light broke out, in the positions indicated in the diagram by the letters A and B, and of the forms of spaces left white. I thereupon noted down the time by the chronometer, and seeing the outburst to be very rapidly on the increase, and being somewhat flurried by the surprise, I hastily ran to call some one to witness the exhibition with me, and on returning within 60 seconds, was mortified to find that it was already much changed and enfeebled. Very shortly afterwards the last trace was gone. The magnetic instruments at Kew were simultaneously disturbed to a great extent.”

(Carrington’s report from Nov. 11, 1859)
The Largest Magnetic Storm on Record: The Carrington Event.

SID onset 1 September 1859 11:15 UT
Mag. storm effect in D and H at 04:50 UT on 2 September 1859.

Transit time = 17:35 hr:min

Reconstruction of the course of the horizontal component during the Carrington event. (Bartels, 1937).

Carrington was aware of the magnetic disturbances that accompanied the flare, but it was not until ~80 years later, in 1937, that Bartels realized the connection between the flare (causing a magnetic crocket) and the large geomagnetic storm caused by the ejection of a cloud of hot gas from the Sun.
The Largest Magnetic Storm on Record: The Carrington Event.

We may describe the terrestrial effects of a solar outburst event by the magnitude of various parameters:

(i) *The amplitude of the Solar Flare Effect/Sudden Ionospheric Disturbance (SFE/SID) event.*

(ii) *The intensity of high-energy solar particle radiation.*

(iii) *The magnitude of the geomagnetic storm scaled by transit time and peak intensity.*

(iv) *The intensity of substorms scaled by the auroral electrojet currents and the latitudinal extent of auroras.*

Within each category we can compare the magnitude of the Carrington storm with other solar-terrestrial disturbances observed later in order to rank the events and obtain a realistic impression of the possible “worst case” effects based on known consequences of recent similar occurrences.

*The following tables and figures are from the references:*
The Largest Magnetic Storm on Record: The Carrington Event.

Solar Flare Effects

We can compare the solar flare effect forming a magnetic "crocket" with other recorded events.

Furthermore, from examination of nitrate isotopes in ice cores, we can estimate the fluence of high-energy solar protons during the Carrington 1859 event.

The 1859 fluence can then be compared with other events recorded either the same way, or by riometer observations of absorption, or by direct satellite measurements.
The Largest Magnetic Storm on Record: The Carrington Event.

### Transit Time


<table>
<thead>
<tr>
<th>Flare date</th>
<th>Transit time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04 Aug. 1972</td>
<td>14.6</td>
</tr>
<tr>
<td>01 Sep. 1859</td>
<td>17.6</td>
</tr>
<tr>
<td>06 Feb. 1946</td>
<td>17.8</td>
</tr>
<tr>
<td>28 Feb. 1941</td>
<td>18.4</td>
</tr>
<tr>
<td>16 Jul. 1959</td>
<td>19.4</td>
</tr>
<tr>
<td>28 Feb. 1942</td>
<td>19.5</td>
</tr>
<tr>
<td>17 Sep. 1941</td>
<td>19.8</td>
</tr>
<tr>
<td>29 Oct. 2003</td>
<td>~20</td>
</tr>
<tr>
<td>28 Oct. 2003</td>
<td>20.3</td>
</tr>
<tr>
<td>15 Apr. 1938</td>
<td>21.2</td>
</tr>
<tr>
<td>12 Nov. 1960</td>
<td>21.2</td>
</tr>
<tr>
<td>16 Jan. 1938</td>
<td>21.8</td>
</tr>
</tbody>
</table>

The transit time is also an important parameter (particularly for forecast). Usually, the larger storms have the fastest transit.

Unfortunately, the existing magnetometers went off-scale in the horizontal component. The estimate (Tsurutani) gives 1600 nT.

### Outstanding Geomagnetic Storm Peak Amplitude

#### Ranges

<table>
<thead>
<tr>
<th>Date</th>
<th>Declination (°)</th>
<th>Horizontal force (nT)</th>
<th>Vertical (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 Sep. 1859</td>
<td>&gt;92</td>
<td>&gt;=625</td>
<td>1500</td>
</tr>
<tr>
<td>04 Feb. 1872</td>
<td>125</td>
<td>800</td>
<td>&gt;950</td>
</tr>
<tr>
<td>17 Nov. 1882</td>
<td>115</td>
<td>&gt;1090</td>
<td>&gt;1060</td>
</tr>
<tr>
<td>31 Oct. 1903</td>
<td>119</td>
<td>1175</td>
<td>1440</td>
</tr>
<tr>
<td>25 Sep. 1909</td>
<td>193</td>
<td>1710</td>
<td>&gt;1080</td>
</tr>
<tr>
<td>14 May 1921</td>
<td>110</td>
<td>&gt;=740</td>
<td>&gt;=460</td>
</tr>
<tr>
<td>25 Jan. 1938</td>
<td>126</td>
<td>1055</td>
<td>570</td>
</tr>
<tr>
<td>16 Apr. 1938</td>
<td>307</td>
<td>1375</td>
<td>500</td>
</tr>
<tr>
<td>24 Mar. 1940</td>
<td>131</td>
<td>1370</td>
<td>1000</td>
</tr>
<tr>
<td>01 Mar. 1941</td>
<td>186</td>
<td>1650</td>
<td>1310</td>
</tr>
<tr>
<td>18 Sep. 1941</td>
<td>123</td>
<td>1250</td>
<td>1115</td>
</tr>
<tr>
<td>28 Mar. 1946</td>
<td>162</td>
<td>1660</td>
<td>920</td>
</tr>
<tr>
<td>21 Sep. 1946</td>
<td>136</td>
<td>925</td>
<td>450</td>
</tr>
</tbody>
</table>

#### Low-latitude Auroras


<table>
<thead>
<tr>
<th>Date</th>
<th>Low-latitude extent</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>04 Feb. 1872</td>
<td>15°</td>
<td>Chapman (1957a,b)</td>
</tr>
<tr>
<td>2 Sep. 1859</td>
<td>20°</td>
<td>Loomis (1859, 1860a,b, 1861); Kimball (1960)</td>
</tr>
<tr>
<td>14 May 1921</td>
<td>30° (see text)</td>
<td>Silverman and Cliver (2001)</td>
</tr>
</tbody>
</table>

DMI October 2010/P.Stauning
Conclusions:

- The September 1859 storms were not markedly larger (if larger at all) than those of the top tens of subsequent great storms.

- However, at the same time, the 1859 space weather event stands alone as the single event that appears at or close to the top of all of the effects lists.

- Still, after 150 years, the first identified space weather event continues to be one of the largest ever recorded – across the activity spectrum.

- And we have also now gained experience of the Space Weather parameters of particular relevance for Geospace, i.e.:
  - magnetic variations
  - high-energy radiation
  - ionospheric disturbances.
2.1. The Geomagnetic Field

The Earth's magnetic field can, in a simplifying approximation, be described as the field from a dipole at the center of the Earth tilted 11.5 degrees with respect to the rotational axis.

Field potential and components:

\[ V = \frac{M \cdot r}{r^3} = -\frac{M \sin \Phi}{r^2} \]

\[ H = \frac{\partial V}{\partial \Phi} = \frac{M \cos \Phi}{r^3} \]

\[ Z = \frac{\partial V}{\partial r} = \frac{2M \sin \Phi}{r^3} \]

Magnetic moment:

\[ M = 7.84 \times 10^{22} \text{ A m}^2 \ (1990) \]
The Geomagnetic Field

The real geomagnetic field is made of several contributions:

**Main ("Internal") Field Sources:**
- Core field (secular variations) ~ 95% of total field
- Crustal field (constant) ~ 2-3%

**External Field Sources:** 1 up to ~5%
- Ionospheric Currents (In E-region at altitudes 100-150 km)
  - Mid-latitude Sq Currents
  - Equatorial Electrojet
  - Auroral Electrojet Currents
  - Transpolar Convection Currents

Magnetospheric Currents:
- Field-aligned Currents (Auroral zones)
- Ring Current (at 4-6 Earth radii)
- Magnetopause and Tail Currents
A better approximation to the real field than the dipole may be obtained by the eccentric dipole model where the assumed dipole is displaced from the centre of the Earth by around 540 km but keep the axis orientation and the magnetic moment.

In a (X, Y, Z) coordinate system where the Z-axis is the Earth’s rotational axis while the X-axis points to the Greenwich meridian, the eccentric dipole was located at (-401.86 km, 300.25 km, 200.61 km) in year 2000.

For the eccentric dipole the northern and southern axial pole positions in 2000 were (83.03°, 266.70°) and (-75.34°, 118.66°), respectively.

The centred and eccentric dipole axial positions should not be confused with the dip pole positions where the actual magnetic field is vertical. In 2000 the northern and southern dip poles were located at (82.66°, -168.60°) and (-66.06°, 128.04°), respectively.

The representation of the geomagnetic field by the centred or the eccentric dipole field is adequate for many space weather applications. For more demanding applications a more precise modelling might be required.
The Geomagnetic Field

The Main Field is usually described through a spherical-harmonic expansion of the magnetic vector potential, e.g.:

\[
V = a \left\{ \sum_{n=1}^{19} \sum_{m=0}^{n} (g_n^m \cos m\phi + h_n^m \sin m\phi) \left( \frac{a}{r} \right)^{n+1} P_n^m(\cos \theta) \\
+ \sum_{n=1}^{2} \sum_{m=0}^{n} (q_n^m \cos m\phi + s_n^m \sin m\phi) \left( \frac{r}{a} \right)^n P_n^m(\cos \theta) \\
+ Dst \cdot \left[ \left( \frac{r}{a} \right) + Q_1 \left( \frac{a}{r} \right)^2 \right] \cdot \\
\left[ \tilde{g}_1^0 P_1^0(\cos \theta) + \left( \tilde{q}_1^1 \cos \phi + \tilde{s}_1^1 \sin \phi \right) P_1^1(\cos \theta) \right] \right\}.
\]

The vector components are given as the partial derivatives of the vector potential with respect to radial distance \( r \), colatitude \( \theta \), and east longitude \( \phi \) (\( \mathbf{B} = -\text{grad} \ V \)).

The parameter \( a \) is radius of the Earth (\( a = \text{Re} \)). The \( P_n^m \) are Schmidt-normalized Legendre functions. The \( g_n^m \), \( h_n^m \), \( q_n^m \), and \( s_n^m \) are tabulated constants.
Geomagnetic Field Models

Tabulations of the most recent field models may be found at various magnetic data centres.

A frequently used version is the International Geomagnetic Reference Field Model (IGRF) derived every 5 years and in time updated to become Definitive Geomagnetic Reference Field models (DGRF).

A graphical representation of the global field magnitude is shown in the Figure. Note the two northern high-intensity regions, one over northern Canada, the other over Siberia.

The southern hemisphere has only one polar high-intensity field region.

Note also the deep minimum, the so-called South Atlantic Anomaly, in the South America-South Atlantic region.

[Stauning, 2002]
2.2. Earth’s Atmosphere and Ionosphere
Earth's Atmosphere and Ionosphere

Ionospheric layers  Atmospheric temperatures  Processes

Atmospheric models are available at:  
http://ccmc.gsfc.nasa.gov/modelweb

[Davies (1990), p.57]
The Ionosphere
<table>
<thead>
<tr>
<th>Ionizing Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Solar EUV radiation</td>
</tr>
<tr>
<td>2. Solar X-ray radiation</td>
</tr>
<tr>
<td>3. Energetic auroral particle radiation</td>
</tr>
<tr>
<td>4. High energy radiation belt particles</td>
</tr>
<tr>
<td>5. High energy solar particles (protons and electrons)</td>
</tr>
<tr>
<td>6. Galactic Cosmic Radiation (CGR) particles</td>
</tr>
</tbody>
</table>
Solar EUV Ionizing Processes

Altitude of Unit Optical Depth

The diagram illustrates the shielding effect of the Earth’s atmosphere at X and EUV wavelengths.

Solar EUV Ionizing Processes

Note that the product of the exponentially decreasing density and the exponentially increasing radiation intensity with altitude produces a peak in the ionization production at a certain height.

\[ I(z) : \text{Intensity of Solar EUV Radiation at altitude } z \]
\[ n(z) : \text{Density of neutral atmosphere} \]
\[ q(z) : \text{Ion production rate} \]

More specifically, the ion production rate can be expressed in the Chapman formula:

\[ q(z) = q_{m,0} \exp\left[1 - \frac{(z - z_{m,0})}{H} - \sec\chi \exp\left(-\frac{(z - z_{m,0})}{H}\right)\right] \]

Where:
- \( q(z) \): Ion production rate at altitude \( z \)
- \( H \): Scale height
- \( q_{m,0} \): Maximum ion production rate at overhead Sun
- \( z_{m,0} \): Altitude for maximum ion production at overhead Sun
- \( \chi \): Solar zenith angle
Conditions of steady-state electron density at mono-chromatic solar EUV, plane-layered atmosphere, and simple recombination processes gives the Chapman electron density profiles:

**Steady-state condition:**

Ion production rate = Ion recombination rate

\[ q(z) = \alpha_{\text{rec}} [N_i] [N_e] = \alpha_{\text{rec}} N^2 \]

Gives for the electron density \( N \):

\[ N = N_{m,0} \exp^{1/2} [1 - (z-z_{m,0})/H - \sec \chi \exp^{-((z-z_{m,0})/H)}] \]

Where:

\( N_{m,0} = \left( \frac{q_{m,0}}{\alpha_{\text{rec}}} \right)^{1/2} \) (maximum density for overhead Sun)

\( H = 2 \frac{R T}{g M} \) (2 times scale height for the neutral atmosphere)
Energetic Particle Ionizing Processes

One should not forget ionization by energetic particle precipitation

Ion production rate

### Ion production energy

<table>
<thead>
<tr>
<th>Target species</th>
<th>Average energy for an ion-pair production $\bar{\varepsilon}$ in eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_2$</td>
<td>35</td>
</tr>
<tr>
<td>$O_2$</td>
<td>32</td>
</tr>
<tr>
<td>$O$</td>
<td>27</td>
</tr>
<tr>
<td>$H_2$</td>
<td>36</td>
</tr>
<tr>
<td>He</td>
<td>45</td>
</tr>
<tr>
<td>Air</td>
<td>34</td>
</tr>
</tbody>
</table>

[Ref.: Brekke (1997), p.461]
The Ionosphere

Variable Electron Density Profiles for:
Night/Day Solar Max/Solar Min

Models for the Ionosphere (densities, composition, temperatures etc.) are available at the web site: http://ccmc.gsfc.nasa.gov/modelweb

[Hargreaves (1992), p.209]
**Definition of the Ionospheric Regions (Structures)**

For convenience, we divide the Ionosphere into four broad regions called D, E, F, and topside. These regions may be further divided into several regularly occurring layers, such as F1 or F2.

**D-Region:**  
The region between about 75 and 95 km above the Earth in which the (relatively weak) ionization is main responsible for absorption of high-frequency radio waves.

**E-Region:**  
The region between about 95 and 150 km above the Earth that marks the height of the regular daytime E-layer. Other subdivisions, isolating separate layers of irregular occurrence within this region, are also labeled with an E prefix, such as the highly variable thin layer, Es (Sporadic E). Ions in this region are mainly O₂⁺.

**F-Region:**  
The region above about 150 km in which the important reflecting layer, F₂, is found. Other layers in this region are also described using the prefix F, such as a temperate-latitude regular stratification, F₁. Ions in the lower part of the F-layer are mainly NO⁺ and predominantly O⁺ in the upper part. The F-layer is the region of primary interest to radio communications.

**Topside:**  
This part of the Ionosphere starts at the height of the maximum density of the F₂ layer of the Ionosphere and extends upward with decreasing density to a transition height where O⁺ ions become less numerous than H⁺ and He⁺. The transition height varies but seldom drops below 500km at night or 800km in the daytime.

[Ref.: http://www.ngdc.noaa.gov/stp/IONO/ionostru.html]
Instrumentation for Geomagnetic Observations
The light beam is deflected from a mirror mounted at a small magnet suspended either in a silk fibre to indicate the direction of the magnetic field (D-magnetometer) or in a quartz fibre that can produce a tension in the suspension to be balanced by the magnetic field strength (H-magnetometer). The light beam is focused to produce a spot at the film wrapped around a rotating drum. A fixed mirror produces a baseline.

The flux-gate principles are illustrated in the left figure. The cores a and b are made from high permeability magnetic material and have windings to carry the excitation current. The sinusoidal excitation current drives the cores into deep saturation in both half period as illustrated in the B-H diagram. A secondary coil picks up the induced signal produced by the flux changes during the short intervals where the coils are not saturated. If there were no external field then the contributions from the two cores would cancel each other to provide a “null-signal”. In most applications a bias current is fed to the secondary coil in order to produce a magnetic field that cancels the external field whereby the null-signal is obtained.

The right figure illustrates the principles used for a practical flux-gate magnetometer. The rectified DC signal from the phase-sensitive detector (PSD) is amplified and used both to neutralize the magnetic field in the fluxgate sensor and to provide an output voltage for recording of the magnetic field variations around the adjustable bias level.

The Fluxgate Magnetometer

The precise and stable magnetometer version now produced at DTU Space (formerly DMI) uses 3 orthogonal fluxgate sensors mounted in groves cut in a marble block (middle photo). The block is cardanically suspended in the transparent enclosure (right photo).

The Theodolite magnetometer in the right photo uses a fluxgate sensor to provide "null" indication when oriented perpendicular to the magnetic field. In the horizontal plane the declination angle can be read-off. When rotated 90° and tilted the inclination can be scaled.
The Proton Precession Magnetometer

Protons have a magnetic moment that causes them to align their magnetic axes either parallel or antiparallel to the ambient magnetic field. The proton magnetometer comprises a bottle with proton-rich fluid such as water or benzene mounted inside a coil. A current impulse through the coil creates an additional magnetic field which causes the proton spin axes to turn into alignment with the new direction of the combined field. When the current is turned off, the proton spin axes will not immediately return to their original direction but will be precessing for a while. The coil may now pick the (weak) precession signal for analysis of its frequency, \( f_p = \left(\gamma_p/2\pi\right)B_0 \), where \( \gamma_p = (q/2mc) \) is the proton gyromagnetic ratio (magnetic moment/angular moment). Thus, the field magnitude is defined solely through atomic constants and the measured frequency through: \( B_0 = 23.4874 \cdot f_p \) [nT]

Proton magnetometer principles. [Forbes (1987), p.87]
3.2. Geospace Current Systems

The magnetic variations measured at ground level are caused by Geospace currents of many different kinds and origins.

The currents can coarsely be divided in three major groups:

- Currents in the ionosphere driven by $V \times B$ electric fields related to thermospheric wind systems (e.g. Sq currents, Equatorial electrojet).

- Currents in the magnetosphere (e.g., Ring current, Tail current)

- Currents in the ionosphere related to electric fields and currents projected from the magnetosphere (e.g., Auroral electrojets, Transpolar convection currents, DPY currents)
The type and strength of magnetic disturbances related to currents in Geospace are strongly dependent on the geophysical location, in particular the geomagnetic latitude. The figure sketches a coarse division in 4 zones of different characteristics.

[Rangarajan (1989), p.325]
Solar Quiet (Sq) Current Systems

The Sq currents are related to the Thermospheric wind system. The prevailing winds are blowing away from the subsolar regions heated by the overhead sun.

[Fesen et al. (1986), in Jacobs vol.3 (1989), p.399]
The Solar Quiet (Sq) current system is driven by the $V \times B$ electric field generated by thermospheric winds that blow away from the equatorial subsolar regions at the dayside.
The Sq currents are particularly intense at the (dip) magnetic equator where they form the Equatorial Electrojet due to the large Cowling conductivities there.
The magnetospheric current systems mostly generated by the Solar wind-Magnetosphere interactions are coupled to the Ionosphere via Region 1 (R1), Region 2 (R2), and Region 0 (R0) field-aligned currents (FAC).
Region 1 currents from the magnetospheric boundary regions flow along field lines down to the auroral ionosphere at the morning side and up from the ionosphere at the night side.
The continuation of the downward R1 FAC at the morning side to feed upward R1 FAC at the evening side creates horizontal ionospheric Pedersen currents (in red) across the Polar Cap.
The continuation of the downward R1 at the morning side to feed upward R1 at the evening side creates horizontal ionospheric Pedersen currents (in red) and Hall currents (in blue) across the Polar Cap. Note that the Hall currents are generated by \( \mathbf{E} \times \mathbf{B} \) convection of the ionosphere moving in the opposite direction (i.e., antisunward across the polar cap).
The downward R1 FAC at the morning side also flow horizontally equatorward in the auroral ionosphere to feed upward Region 2 FAC currents to the Ring current region. At the evening side the downward R2 FAC currents from the Ring current region flow across the auroral ionosphere as horizontal Pedersen currents to feed the upward R1 FAC currents.
In addition to the connecting Pedersen currents, the potential differences between the downward R1 and the upward R2 currents at the morning side or between the downward R2 and the upward R1 currents at the evening side drive strong ionospheric convection and related Hall currents in the auroral ionosphere. These Hall currents (in blue) are the sunward Auroral Electrojet currents, i.e., westward at the morning and eastward at the evening side.
During conditions with a strong azimuthal component, $B_y$, of the Interplanetary Magnetic Field (IMF), a special Region 0 (R0) field-aligned current system appears. The R0 currents connect from the magnetospheric Cusp region to the ionosphere at noon at around 75° magnetic latitude. The current direction is upward in the northern hemisphere for positive values of IMF $B_y$ and downward in the southern. The R0 currents are connected to the R1 currents of relevant polarity by horizontal Pedersen currents across the ionospheric Cusp region.
The potential differences between the R0 and R1 currents drive strong transverse convection and associated Hall currents (in blue signature) in the ionospheric Cusp region at around local noon and at magnetic latitudes around 75°, i.e., poleward of the auroral region. These Hall currents are also named DPY currents (Polar Disturbance related to IMF By).
When the possible effects on high-latitude ground-based magnetic observations are being evaluated, then the Fukushima theorem is very useful.

The theorem states that with a horizontally stratified, homogeneous ionosphere, with a system of parallel, infinitely extended, uniform sheets of upward and downward FAC connected by horizontal Pedersen currents, and with induced Hall currents flowing in-between the FAC sheets, then the magnetic effects below (outside) the current system will be controlled by the Hall currents only, since the magnetic effects of the FAC and Pedersen currents cancel each other.

The theorem is a fair (not perfect) approximation in most real cases. Thus, the ground magnetic effects in the polar and auroral regions are mainly related to the transpolar and auroral electrojet convection-related Hall currents, respectively.

The Hall currents are shown in blue signature in the preceding slides. These currents form horizontal closed vortex-like circuits in the polar and auroral ionosphere.
3.3. The Variable Geomagnetic Disturbance Fields

The effects of the variable external field sources are often described through various disturbance indices:

\( K \) : 3-hourly magnetic activity index defined from min-to-max amplitude in the variations in the horizontal field component

\( Kp \) : Planetary K-index. Average of K-indices at mid-latitude observatories

\( Dst \) : Ring current index derived from magnetic variations at near-equatorial observatories.

\( AE \) : Auroral Electrojet indices (AL, AU, AE, AO) derived from magnetic variations at a longitudinal array of observatories in the auroral regions.

\( PC \) : Polar Cap indices (PCN and PCS) derived from the magnetic variations recorded at the observatories Thule in the northern and Vostok in the southern central polar cap.
Magnetic Indices K and Kp

The 3-hourly so-called “K” index was introduced by J. Bartels in 1939 in order to describe the degree of magnetic disturbance (above the regular daily variation) observed in magnetometer recordings.

The name (K) was derived from the German word “Kennziffer”. The index value is derived from the amplitude range beyond the regular daily variation of the most disturbed of all three magnetic elements (H, D, Z) in a three-hourly interval (00-03, 03-06…UT).

The amplitude range can be derived as the distance between the smooth curves of shape equal to the quiet daily curve (QDC) just touching the recorded trace from above and from below. After scaling, the 3-hourly range measured in nT is converted to a single number between 0 and 9 using a scale with logarithmically spaced steps for the amplitude range.

The Kp (Planetary K) index is formed as the average value of the K-indices supplied from a range of mid-latitude magnetic observatories of high quality.

The K-index is a measure of the general geomagnetic activity. The value is strongly dependent on conditions in the solar wind flowing out from the rotating Sun.

When displayed in stacked sections for complete 27 days solar rotation intervals then the active regions at the Sun will produce repetitive structures.

The official Kp index is calculated by the GeoForschungsZentrum (GFZ) in Potsdam on basis of final geomagnetic data. Hence the index is not available in the current year.

[Rangajaran (1989), p.335]
Magnetic Indices K and Kp

An on-line real-time preliminary Kp index is constructed by NOAA Space Weather Prediction Center based on a limited selection of observatories.

The preliminary Kp index is used to specify the severity G1 – G5 of possible storm conditions according to the Kp index value, i.e.:

Kp = 5 → G1 ….. Kp=9 → G5

The NOAA Prediction Center presents Kp index values in diagrams for a 3-days interval. The latest values are automatically inserted as they become available. The above example event ("Bastille event") started with an X-ray flare of class X (very large) at 10 UT on 14 July, 2000, and was accompanied by a very intense radiation of high-energy solar protons.

http://www.swpc.noaa.gov/rt_plots/kp_3d.html
**Magnetic Index Dst**

**Dst index.** The Dst (Disturbance Storm Time) monitors the world wide magnetic storm level. The index represents the axially symmetric disturbance magnetic field at the dipole equator on the Earth's surface. Major disturbances in Dst are negative, i.e., decreases in the geomagnetic field produced mainly by the equatorial current system in the magnetosphere, usually referred to as the ring current, which flows clockwise around the Earth in the equatorial plane.

The ring current results from the differential gradient and curvature drifts of electrons and protons in the Near-Earth region at 4-6 Earth radii distance and its strength is coupled to the solar wind conditions. The neutral sheet current flowing across the magnetospheric tail makes a small additional contribution to field decreases near the Earth.

Positive variations in Dst are mostly caused by the compression of the magnetosphere from solar wind pressure increases (e.g., at SSC at the arrival of the front of a CME). Negative Dst values indicate a magnetic storm is in progress (e.g., the main phase during CME events), the more negative Dst is, the more intense the magnetic storm.
The Dst values are derived on basis of geomagnetic data from a small array of longitudinally distributed observatories at low latitudes but at safe distance from the strong Equatorial electrojet.

Final Dst values are calculated by the WDC-C2 in Kyoto and made available at their web site (http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html).

Real-time preliminary Dst values are available on-line at the link: http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html. An example of recent Dst values are given in the above plot for October, 2010. Note in the above example the minor storm on 11-12 Oct. 2010.
Various attempts have been made to forecast Dst index values from measurements of solar wind parameters. Burton et al. (1975) found that the Dst index could be predicted quite successfully using the following formula.

\[
d(Dst^*)/dt = F(E) - a Dst^*
\]

where

- \( Dst^* = Dst - b \sqrt{P_{\text{dyn}}} + c \),
- \( F(E) = d \text{ (Ey-0.5)} \) for \( \text{Ey} > 0.5 \text{ mV/m} \) or else \( F(E) = 0 \).
- \( a = 3.6 \times 10^{-5} /\text{s} \)
- \( b = 0.20 \text{ nT}/\sqrt{\text{(eV/cm}^3)} \)
- \( c = 20 \text{ nT} \)
- \( d = -1.5 \times 10^{-3} \text{ nT}/(\text{s mV/m}) \)

In this equation \( Dst^* \) represents the Dst value from the injected ring current only. The constant \( b \) is a measure of the Dst response to solar wind dynamic pressure while \( c \) is a measure of the quiet time ring current.

\( F(E) \) is the ring current injection rate and depends upon the dawn to dusk solar wind electric field, \( \text{Ey} \), which is the negative product of the solar wind speed, \( V_{\text{SW}} \), and the southward component, \( B_z \), of the interplanetary magnetic field.

The constant \( d \) is a measure of the response of the injection rate to \( \text{Ey} \), which is assumed to be linear, and the parameter \( a \) is a measure of ring current decay, the value of which corresponds to an e-folding time of 7.7 hours. Updated calculations of the predicted Dst index using ACE satellite data (http://www.srl.caltech.edu/ACE/) and a slightly improved formula are available at: http://sprg.ssl.berkeley.edu/dst_index/images/cumulative.gif.
A neural network algorithm is used for 1-hr forecasts of Dst based also on ACE satellite data in the ESA SWENET project, GIFINT. The results are available at http://gifint ifsi rm.cnr.it. As noted above, it is important to take into account that the satellite or its instruments (e.g., the solar wind detectors) could be disabled by the high-energy radiation that often accompanies major solar flares and outbursts (CMEs).

An example of real-time data from ACE (http://www.srl.caltech.edu/ACE) from 15 July 2000 is shown above. Note the depression of $V_{SW}$ up to 16 UT on 15 July 2000. The depression was caused by the radiation of high-energy solar protons emitted from the active flare region starting at 10 UT on 14 July 2000 (the “Bastille Event”).
The Auroral Electrojet (AE) indices were developed by Davis and Sugiura (1966) to characterize the strength of the eastward and westward electrojet currents.

The calculations of AE indices are based on measurements of the horizontal magnetic component from a range of observatories located in the auroral zone and well distributed in longitude.

The AU and AL index values are defined as the amplitudes in nT of the upper and lower envelope, respectively, of the ensemble of magnetic recordings corrected for the regular daily variation (QDC). Thus, the AU values are mostly defined from observations in the afternoon sector of the auroral oval while the AL values are defined from the magnetic data from the morning to midnight sector of the oval.

The AE values are defined as the difference, \( AE = AU - AL \), while the AO index values are defined as the average, \( AO = 0.5 \ (AU + AL) \).

Initially, the index values were calculated as 2.5 min samples. Now, they are also provided at 1-min resolution. Presently, the basic net of stations comprises 12 observatories.
The auroral electrojet indices are calculated by the World Data Center (WDC-C2) in Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/aedir/index.html). Real-time index values are provided on-line from the Kyoto data center in numerical or graphical form on basis of raw data from the available observatories. A recent example of actual on-line real-time AU, AL, AE, and AO index data is displayed above.
Magnetic Indices PCN and PCS

The polar cap indices, PCN for the northern polar cap and PCS for the southern, are mainly determined by the intensity of the antisunward transpolar convection-related Hall current system with minor contributions from the auroral electrojet currents.

Presently, the indices are derived from the magnetic recordings made at Thule (PCN) and Vostok (PCS) following a scheme originally devised by Troshichev et al. (1988).

The basis for the index is the assumption that the transpolar convection and hence the Hall currents are mainly driven by the so-called “geo-effective” (or “merging”) solar wind electric field (Kan and Lee, 1979):

$$E_m = V_{SW}B_T \sin^2(\theta/2).$$

This parameter is a combination of the solar wind velocity, $V_{SW}$, and the transverse component, $B_T$, ($B_T = (B_Y^2 + B_Z^2)^{1/2}$) of the interplanetary magnetic field.

An example of polar cap electric potential, convection and magnetic disturbance patterns are provided above. (after Friis-Christensen et al., 1985). The arrow indicates the direction of the magnetic variation, $\Delta F$. 

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Magnetic Indices PCN and PCS

At ground level the uniform transpolar currents generate horizontal magnetic variations, $\Delta F$, that are perpendicular to the current direction.

In order to enhance the relations to the solar wind geo-effective electric field and suppress other contributions, then the magnetic disturbance vectors are projected to a so-called “optimum direction” derived by searching optimum (statistical) correlation between the scalar value, $\Delta F_{\text{PROJ}}$, of the projected vector and $E_m$.

From (statistical) regression analysis the best linear fit between $\Delta F_{\text{PROJ}}$ (in nT) and $E_m$ (in mV/m) is determined:

$$\Delta F_{\text{PROJ}} \sim S \cdot E_m + \Delta F_I$$

where $S$ is the “slope” and $\Delta F_I$ the “intercept”. Now, this equation is inverted to provide an estimate of the parameter, PC, that results from using actual values of the projected magnetic variations:

$$PC = \frac{\Delta F_{\text{PROJ}} - \Delta F_I}{S} \sim E_m \text{ [in mV/m]}$$

The three parameters, optimum angle, slope and intercept are provided in tables of values for each hour of the day and each month of the year.

In the recent scheme (Troshichev et al., 2006), the magnetic variations are now counted from the quiet level (the QDC).
The PC indices are usually provided in 1-min resolution.

The PCN and PCS indices are not (yet) adopted as official IAGA indices, the approval is pending.

PCN index values (1975-2009) are available on request from the Danish Meteorological Institute, DMI, (pst@dmi.dk).

Graphical displays of recent PCN values are available at http://wdcc1.dmi.dk/pcnu/pcnu.html.

PCS index values (1996-2010) are available from the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia (olegro@aari.nw.ru).

Recent PCS values are displayed on-line at http://www.aari.nw.ru/clgmi/geophys/pc_main.htm

An example is shown above. Note the green line at the value 2.0. PC values above this value signals imminent auroral substorm conditions.
In calculations of the equivalent Dst ring current index using the above Burton et al. (1975) formula, the PC indices may provide as fair an approximation to the real Dst index values as the solar wind Em.

An example is shown for the large October 2003 storm. The Dst index is shown in black line with dots. The solar wind electric field and the derived Dst index in red. The PC index in blue and the derived Dst index in blue line with dots.

The strong solar proton radiation disabled the ACE solar wind velocity instrument at an early time in the event. Hence the Em and the equivalent Dst values derived from Em are missing during most of the event. The same adverse conditions apply to similar forecast calculations of the auroral electrojet indices.
The two most serious problems related to geomagnetic variations are power grid disturbances and pipeline corrosion. Both are related to the Geomagnetically Induced Currents (GIC) that flow in all conducting structures at variations in the ambient magnetic field. The figure illustrates the situation for a HV power line extended below a variable auroral electrojet current.

The left figures display PCN index (upper panels), auroral electrojet indices AU (blue) and AL (red line) (middle panel), the horizontal (H) component of the magnetograms from Brorfelde (bottom panel). Power line disruptions in Sweden are marked by black triangles.

It is evident in the figure that the power line disturbances occur at the large and sudden magnetic disturbances indicated by the excursions particularly in the AL index.

These events, in turn, occur during enhanced PCN index values above 10 (“red alert”).
Links and References

Links and further reading:

Kp from NOAA Space Weather Prediction Center: (http://www.swpc.noaa.gov/rt_plots/kp_3d.html)

Kp from GeoForschungs-Zentrum (GFZ), Potsdam (http://www-app3.gfz-potsdam.de/kp_index/index.html)


Real-time AE values: http://wdc.kugi.kyoto-u.ac.jp/ae_realtime/today/today.html


ACE satellite data: http://www.srl.caltech.edu/ACE/

Improved Dst formula: http://sprg.ssl.berkeley.edu/dst_index/images/cumulative.gif.

Recent PCS values: http://www.aari.nw.ru/clgmi/geophys/pc_main.htm

ESA SWENET project, GIFINT: http://gifint.ifsi.rm.cnr.it/.

General Space Weather data: http://www.swpc.noaa.gov/today.html#satenv
Links and References

Magnetic data links
International Monitor for Auroral Geomagnetic Effects (IMAGE):
http://www.ava.fmi.fi/image/data.html
Nordic magnetometer data at Tromsø Geophysical Observatory (TGO):
http://geo.phys.uit.no
Russian magnetometer data: http://www.aari.nw.ru/clgmi/geophys/pc_main.htm
210° Magnetic Meridian real-time data: http://magdas.serc.kyushu-u.ac.jp/qdata/index.php
Geophysical Institute Magnetometer Array (GIMA): http://magnet.asf.alaska.edu
Magnetometer Array for Cusp and Cleft Studies (MACCS), Realtime dataplots:
http://space.augsburg.edu/space/MaccsHome.html
Boulder Magnetometer realtime: http://www.swpc.noaa.gov/rt_plots/bou_12h.html
Time History of Events and Macroscale Interactions During Substorms (THEMIS):
http://themis.ssl.berkeley.edu
Canadian Magnetic Observatory System (CANMOS) data:
http://gsc.nrcan.gc.ca/geomag/data/index_e.php
Realtime data:
http://geomag.nrcan.gc.ca/common_apps/auto_generated_products/stackplot_e.png
SuperMAG: http://supermag.jhuapl.edu/index.html
SuperMAG data base: http://supermag.jhuapl.edu/inventory/index.html
References

Easy reading:
www.sec.noaa.gov/Education/index.html

Models:
http://ccmc.gsfc.nasa.gov/modelweb

Reference book:

Main field models:

Magnetic instruments:

Indices:

Advanced reading:
Handbook of Geophysics and Space Environment, AFGRL, 1985