Space Weather and Satellite System Interaction Lecture 4: Space and Earth Electromagnetism

Assoc. Prof. Ir. Dr. Mohamad Huzaimy Jusoh

huzaimy.uitm@gmail.com
1. Basic concept of Geomagnetism
2. Measurement of Geomagnetic Field
3. Temporal variations of Geomagnetic Field
4. Particle movement in Geomagnetic Field
5. Theoretical model of the earth’s magnetic field
6. Variations in the Earth’s Magnetic Field
Magnetic Field Lines

Magnetic field lines are continuous.
E field lines begin and end on charges.
There are no magnetic charges (monopoles) so B field lines *never* begin or end
Earth’s magnetic fields

The Earth's magnetic field is both expansive and complicated. It is generated by electric currents that are deep within the Earth and high above the surface. All of these currents contribute to the total geomagnetic field. In some ways, one can consider the Earth's magnetic field, measured at a particular instance and at a particular location, to be the superposition of symptoms of a myriad of physical processes occurring everywhere else in the world.

Magnetic fields are vectors: they have a strength (magnitude) and a direction just like velocity.

From USGS web site (http://geomag.usgs.gov/intro.html)
Magnetic Field of the Earth, $B$

Also a magnetic dipole!

The strength of a magnetic field is the magnetic flux density, $B \ (T)$

$$1 \text{Tesla} = 1 \frac{N}{A \times m}$$

$$1 \ T = 10,000 \text{ Gauss}$$
North and south poles are the points of intersection of the axis of the magnetic field and the surface of the Earth.

The axis of the magnetic field is at a small angle to the axis of rotation: termed the **magnetic declination**.

The magnetic poles moves about the geographic poles: termed **secular variation** in the magnetic pole position.

Angle of magnetic pole – angle of geographic pole = magnetic declination
Magnetic Elements

To measure the direction and intensity of the field, there are seven parameters that are used:

1. Declination (D)
2. Inclination (I)
3. Horizontal Intensity (H) - Intensity in the xy-plane
4. North component (X)
5. East component (Y)
6. Vertical Intensity (Z) - Intensity in the z direction
7. Total Intensity (F) - magnitude of the intensity

\[ H = \sqrt{X^2 + Y^2} \]

\[ F^2 = X^2 + Y^2 + Z^2 \]
The geomagnetic coordinate system describes the way the magnetic field is pointing by defining:

- **X**: the strength of the magnetic field in the direction of Earth’s magnetic north pole
- **Y**: the strength of the magnetic field in the magnetic east direction (90 deg from X and toward east)
- **Z**: the strength of the magnetic field pointing down (90 deg from both X and Y – right hand rule!)
Compass-type (HDZ)

The compass-type coordinate system describes the way the magnetic field is pointing by defining:

- **H**: the strength of the magnetic field in the plane horizontal to Earth’s surface (horizontal plane)
- **D**: the angle between geographical north (X) and the direction of the magnetic field in the horizontal plane
- **Z**: the strength of the magnetic field pointing down
- **B**: the strength of the total magnetic field value

\[
B^2 = X^2 + Y^2 + Z^2
\]
\[
B^2 = H^2 + Z^2
\]
Measurement of Geomagnetic Field

- Geomagnetic measurements is the quantitative determination of the Earth’s magnetic field elements
- This is done by using magnetic instruments, called magnetometers
Danish FGM-FGE (Used by British Geological Survey)

GEMS didD (in Market)

MAGDAS-9 (used by Langkawi National Observatory)
Geomagnetic Field Observations

MAGDAS/CPMN
(MAGnetic Data Acquisition System/Circum-pan Pacific Magnetometer Network)

Magnetic Equator

INTERMAGNET

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL
Daily Magnetic variation

An example of amplitude-time records of ordinary (upper; MAGDAS data (1)) and induction-type (bottom; MAGDAS data (2)) variations observed at the Kyuju station.
Temporal Variations in Earth’s magnetic field

**Secular Variations** - Long-term (decades) changes caused by fluid motion in Earth's outer core.

**Diurnal Variations** - Daily variations related to interaction of the geomagnetic field with solar wind.

**Magnetic Storms** - Intense (1000 nT), irregular and unpredictable variations associated with solar flares.

http://apollo.lsc.vsc.edu/classes/met130/notes/chapter2/aurora_magnetosphere.html
Secular Variation in Earth's magnetic field since 1600

http://swdcwww.kugi.kyoto-u.ac.jp/igrf/
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http://swdcwww.kugi.kyoto-u.ac.jp/igrf/
Solar Wind (SW)

When changes in the solar wind, such as changes due to Coronal Mass Ejections, hit Earth’s magnetosphere, the magnetospheric currents will change. These currents will cause changes in our magnetometer data.

We will focus on ring currents and auroral currents.
Effects of Ring Current on the Mag Data

- Charged particles circle Earth at about 10 Re (60,000 km) from Earth’s surface near the equator.
- The electrons and the ions move in opposite directions, creating the ring current.
- When disturbed, the ring current *weakens* Earth’s magnetic field even more. This is called a *magnetic storm*.
Ground magnetic pulsation

Table: IAGA classification of ULF waves in 1964

<table>
<thead>
<tr>
<th>Period (sec)</th>
<th>Pc 1</th>
<th>Pc 2</th>
<th>Pc 3</th>
<th>Pc 4</th>
<th>Pc 5</th>
<th>Pi 1</th>
<th>Pi 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2-5</td>
<td>200-5000</td>
<td>100-200</td>
<td>10-45</td>
<td>45-150</td>
<td>150-600</td>
<td>1-40</td>
<td>40-150</td>
</tr>
<tr>
<td>5-10</td>
<td>200-5000</td>
<td>100-200</td>
<td>10-45</td>
<td>45-150</td>
<td>150-600</td>
<td>1-40</td>
<td>40-150</td>
</tr>
<tr>
<td>10-45</td>
<td>200-5000</td>
<td>100-200</td>
<td>10-45</td>
<td>45-150</td>
<td>150-600</td>
<td>1-40</td>
<td>40-150</td>
</tr>
<tr>
<td>45-150</td>
<td>200-5000</td>
<td>100-200</td>
<td>10-45</td>
<td>45-150</td>
<td>150-600</td>
<td>1-40</td>
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</tr>
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<td>10-45</td>
<td>45-150</td>
<td>150-600</td>
<td>1-40</td>
<td>40-150</td>
</tr>
</tbody>
</table>

Table: Dependence of the skin depth in the lithosphere

<table>
<thead>
<tr>
<th>Skin depth δ (km)</th>
<th>Conductivity σ (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10^-1</td>
</tr>
<tr>
<td>sec</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>min</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

Yumoto et. al, 2009
How Does this Impact the Grid?

1. Ionized particles bombard the Earth
2. Earth’s magnetic field disrupted
   – Electric potential induced on earth’s surface
3. DC current (GIC) induced in neutral of transmission lines
4. Transformer saturation
   – Overheating -> damage (especially older equipment)
   – Produce harmonics
   – Increased reactive power requirements
5. Potential for system collapse - blackouts
Major Historical Events

- Sept. 1859 “Super Storm”
  - Largest GMD event ever recorded
  - 2x stronger than 1921 storm

- May 1921
  - 10x stronger than 1989 storm
  - Northern lights seen from Puerto Rico
  - “100 year storm” - debatable

- March 1989
  - Significant grid impacts
  - Hydro Quebec blackout
Variations in the Earth’s Magnetic Field

1. Exogenous events
2. Endogenous Events
## Date and event of the analyzed data

<table>
<thead>
<tr>
<th>EVENT</th>
<th>STATION</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>At Earth equator, low latitude (Solar Wind Dynamic Pressure &amp; Solar Wind Speed)</td>
<td>Davao, Philippine</td>
<td>1 – 5 June 2011</td>
</tr>
<tr>
<td><strong>EXOGENOUS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At Mid Latitude (Solar Wind Input Energy)</td>
<td>Paratunka, Russia</td>
<td>1 – 5 June 2011</td>
</tr>
<tr>
<td>At High Latitude (Solar Wind Input Energy)</td>
<td>Magadan, Russia</td>
<td>1 – 5 June 2011</td>
</tr>
<tr>
<td>Human Activities</td>
<td>Amami-Oh-Shima, Japan</td>
<td>20-26 January 2007</td>
</tr>
<tr>
<td><strong>ENDOGENOUS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earthquake</td>
<td>Hualien, China</td>
<td>18-20 December 2012</td>
</tr>
</tbody>
</table>
Variations in the Earth’s Magnetic Field (1)

Exogenous event
Pc2 show no variation. 
Pc3 show very small variation up to 2nT. 
Pc4 show strong variation with value of geomagnetic pulsation up to 10nT. 
Pc5 show the strongest variation with higher value and more frequent variation of geomagnetic pulsation with value reach up 15nT.
HIGH LATITUDE VS MID LATITUDE

MAGADAN, RUSSIA 59.97 ° (HIGH LATITUDE)

PARATUNKA, RUSSIA 52.94 ° (MID LATITUDE)
- **Pc2** show no variation at both mid and high latitude.
- **Pc3** show very small variation up to **2nT** at both mid and high latitude.
- **Pc4** show strong variation with value of geomagnetic pulsation up to **3nT** at mid latitude whereas amplitude value up to **10nT** at high latitude.
- **Pc5** show the strongest variation with higher value reach up **10nT** at mid latitude whereas amplitude value up to **15nT** at high latitude.
- **High** latitude yields more strong amplitude of geomagnetic pulsation

**MID LATITUDE (PARATUNKA, RUSSIA)**

**HIGH LATITUDE (MAGADAN, RUSSIA)**
LOW LATITUDE

DAVAO, PHILLIPINE
7.00°
(LOW LATITUDE)
DAVAO, PHILLIPINE

- Pc2 show no variation.
- Pc3 show very small variation value up to 5nT.
- Pc4 show strong variation with value of geomagnetic pulsation up to 18nT.
- Pc5 show the strongest variation of geomagnetic pulsation with value reach up 20nT.
Variations in the Earth’s Magnetic Field (2)

- Endogenous Events
  - Human Activities
  - Earthquake
Strongest variation on the first 12 hours with value of geomagnetic pulsation up to 2nT.
- Pc2 and Pc3 show the strongest variation value up to 2nT.
- Pc4 show weaker variation of geomagnetic pulsation compare with Pc2 and Pc3 with value up to 2nT.
- Pc5 show the weakest variation of geomagnetic pulsation with amplitude value reach up to 0.5nT.
EARTHQUAKE

DATE: 19 DEC 2009
TIME: 13:12:16 UT
MAGNITUDE: 6.4

- H component shows a declination of amplitude.
- D component variation is the same pattern.
- Z component shows an increasing of amplitude.

HLN on December 2009
## Comparison

<table>
<thead>
<tr>
<th>EXOGENOUS EVENTS</th>
<th>ENDOGENOUS EVENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Geomagnetic pulsation of higher continuous pulsation with very low range of frequency yield significant result</td>
<td></td>
</tr>
<tr>
<td>• <strong>Pc5</strong> show the most significant variation starting from <strong>Pc3</strong> and <strong>Pc4</strong></td>
<td></td>
</tr>
<tr>
<td>• <strong>Pc2</strong> only affected on severe cases</td>
<td></td>
</tr>
<tr>
<td>• Geomagnetic pulsation shows the most compelling variation is at lower geomagnetic pulsation with high range of frequency band</td>
<td></td>
</tr>
<tr>
<td>• <strong>Pc2</strong> show the most significant variation</td>
<td></td>
</tr>
<tr>
<td>• <strong>Pc5</strong> only affected on severe cases</td>
<td></td>
</tr>
<tr>
<td>• Z-component show the most compelling result specifically for human activities</td>
<td></td>
</tr>
<tr>
<td>• Further study should be conducted to prove the relationship between underground activities occur with ULF variation for Earthquake events.</td>
<td></td>
</tr>
</tbody>
</table>
Variation of Earthquake depth with Solar cycle

- Each sunspot number (SSN) level is categorized for every 20 SSN.
- Highest number of EQ (both ranges) are observed during lowest range of SSN (0-20).
- A small increase in the number of EQ (both ranges) at SSN level 100-120.
Anomalous ULF emissions during EQ events (Emad et. al, 2012)

• Higher variation in the daily average of Pc3 amplitude (10-45s) detected a few months before the EQ events; on 15 Aug 2007 and 29 Mar 2008.

• The Pc3 amplitude ratio (ZPc3/HPc3) also shows a good agreement with higher depression ratio for both EQ events.
Geomagnetic Indices

PC Index
- Measures geomagnetic disturbances at the polar cap.
- Measures the energy inflow from the solar wind into the Earth's magnetosphere.

AE Index
- Measure of auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval.
- AE Index are measured from the northern hemisphere auroral zone.

Kp Index
- The Kp-index quantifies disturbances in the horizontal component of Earth's magnetic field.
- Kp Index is obtained from a number of magnetometer stations at mid-latitudes.

Dst Index
- Measure of geomagnetic activity used to assess the severity of magnetic storms.
- Dst Index is obtained from magnetometer stations near the equator.

Geomagnetic world map on which indicate the positions belonging to the different networks used in deriving geomagnetic indices.
The magnetic variations related to the Polar Cap ionospheric convection systems can be used to indicate the varying intensities of the solar wind encounter with the Magnetosphere.

However, the amplitudes of the magnetic variations observed in the Polar Cap depend strongly on observatory local time, season and location. This complicates their use in Space Weather applications.

To be useful for Space Weather issues, the magnetic variations should be converted into values that are independent of local time, season and observatory. This is the basis for developing a PC index.
Kp Index

- The Estimated 3-hour Planetary Kp-index is derived at the NOAA Space Weather Prediction Center using data from the following ground-based magnetometers: Sitka, Alaska; Meanook, Canada; Ottawa, Canada; Fredericksburg, Virginia; Hartland, UK; Wingst, Germany; Niemegk, Germany; and Canberra, Australia.

- Kp index is a numerical value calculated from a global distribution of magnetometers at mid-latitudes that allows scientists to keep track of the level of geomagnetic activity on a given day.

- Kp varies from 0-9 (log scale)

- Kp is affected by many currents including the ring current and auroral currents.

- The stronger the ring current and/or auroral currents, the higher the Kp index value.
Kp Index = 1

X (nT): 13490  19000  17835  21630

Laura Peticolas, THEMIS
Kp Index = 7

X (nT)

18940

Y (nT)

17745

Z (nT)

21585

Laura Peticolas, THEMIS
Assumption: The strength of a geomagnetic storm can be studied from the changes of the ring current.
Geomagnetic storms

**SW Effects**

Geomagnetic storms:

Disturbances in the Solar Wind and Earth’s Magnetosphere coupled system, caused by solar activity

- Energetic particles are transferred from the solar wind to the magnetosphere

**Criterion:**

- $B_z < 0$: Southward magnetic field

  magnetic reconnection between the solar wind and the magnetosphere
**BURTON’S MODEL**

\[
\frac{d(Dst^*)}{dt} = F(E) - aDst^* \\
Dst^* = Dst - b(P_{dyn})^{1/2} +
\]

- **b**: Measures the changes of the \(P_{dyn}\) of the Solar Wind.
- **c**: Measures the magnetic field at the quiet time of the ring current.
- **F(E)**: Is the ring current injection rate and depends only from the \(E_y\) (y-component of solar wind’s electric field) \(E_y = -(V\times B)_y\).
- **d**: Measures the response of the injection rate.
- **1/\(\alpha\)**: Measures the life-time of particles into the ring current.

\[
F(E) = \begin{cases} 
O & \text{if } Ey < 0.5 \text{V} / m \\
\frac{d(E_y - 0.5)(P_{dyn})^{1/2}}{Ey > 0.5 \text{V} / m} & \text{if } \end{cases}
\]

\[\alpha \rightarrow 3 \text{ ñ 5 hours}, Ey > 4 \text{mV/m} \]
\[\alpha \rightarrow 7,7 \text{ hours}, Ey < 4 \text{mV/m} \]
\[b = 0.20 \text{ nT/(eV/cm}^3\}^{1/2} \]
\[c = 20 \text{ nT} \]
\[d = 1,2 \times 10^{-3} \text{ nT} / (\text{smV/m}) \]

I.Antoniadou
Ionosphere Effects

From: http://geomag.usgs.gov/intro.html:

Shown is a stackplot of 4 days of the horizontal magnetic field strength (H) as measured by US Geological Survey (USGS) magnetometers during magnetically quiet conditions in early January 2003.

- High latitudes: aurora currents
- Mid- and low-latitudes: the regular diurnal magnetic-field variation from large-scale daytime electric currents in the Earth's ionosphere.
The Earth’s magnetic field is not symmetric

South Atlantic Anomaly (also called Brazilian Anomaly or Capetown Anomaly) is a lowest magnetic field region located at 26S, 53W.
**SAA** is frequently said is due to the

The **tilt of the dipole axis** with respect to the rotational axis

And due to the **displacement of the geomagnetic axis** from the center of the Earth

(Nichitiu, 2004)
Thank you