GEOMAGNETIC INDUCTION

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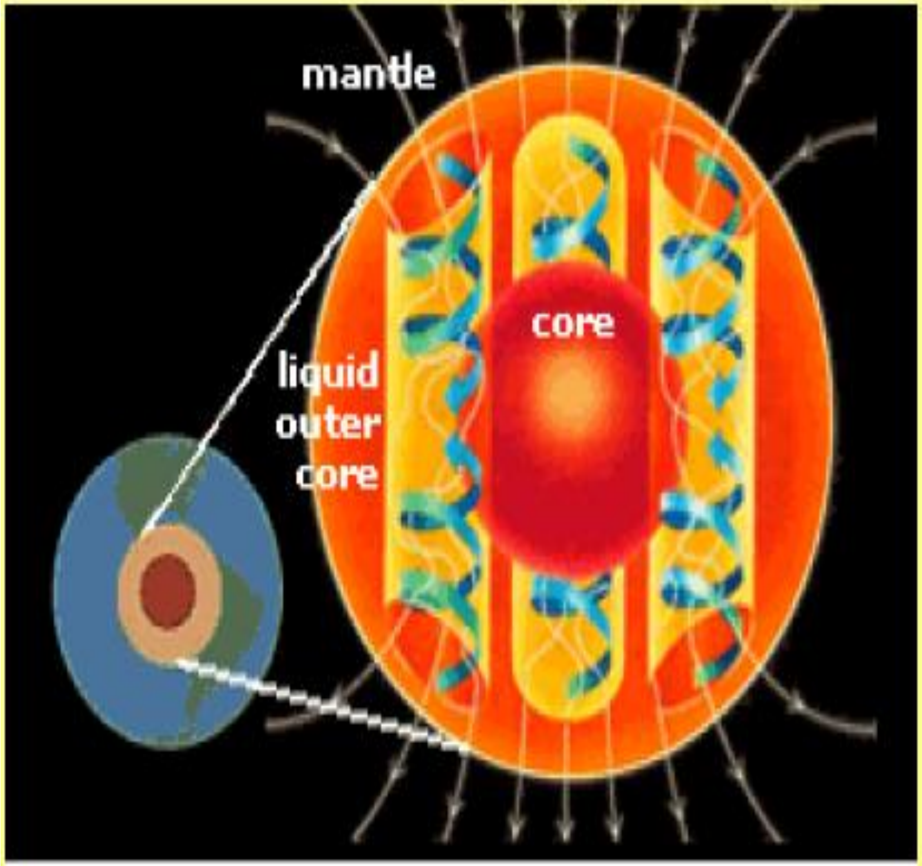
Sources of Geomagnetic Field

1) Core motion: Convection motion of the conducting fluid core of the Earth constitutes a self exciting dynamo.

90% of the Earth magnetic field is from the core field. The outer core is Fe+Ni alloy that is conducting iron.

The presence of the conducting iron and the magnetic field induce electric current and the electric current produce magnetic field.



Lines show a possible configuration of fluid flow and magnetic field in the liquid outer core

(2) Crustal Magnetization: Residual permanent magnetism exists in the crust of the Earth.

(3) Solar electromagnetic radiation : Atmospheric wind (produced by solar heating) move charge particles (produced ionizing radiation) ;this constitute an ionospheric current which generates a field.

(4) Gravitational : The gravitational field of the Sun and moon produce a tidal motion of air masses that generates a field in the same way a does the air motion from solar heating.

(5) Solar corpuscular radiation and interplanetary field: A number of the field contributions arise directly or indirectly from the interaction of the solar wind and its imbedded magnetic field with the main field of the Earth.

There are others sources that do not contribute appreciably ; examples
Are the mantle of the Earth and energetic cosmic rays.

Units of Magnetic Field

The geomagnetic field is a vector that has both magnetic and direction.

(i) Oersted is a magnetic intensity of non varying field (e.g. a permanent magnet)

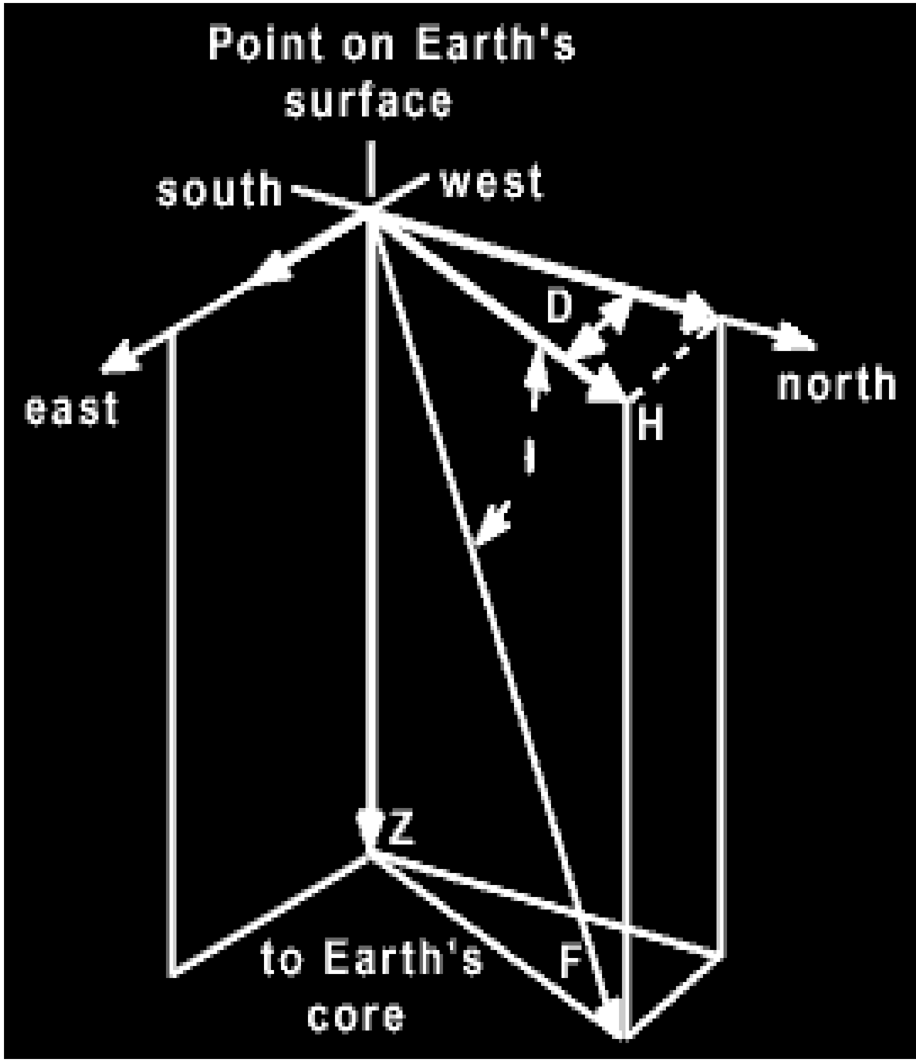
(ii) Gauss is a magnetic intensity of induced field by electric current

1 Tesla=10^4 gauss

Components of the Magnetic Field

The total magnetic field can be divided into several components:

- **Declination (D) indicates the difference, in degrees, between the headings of true north and magnetic north.**
- **Inclination (I) is the angle, in degrees, of the magnetic field above or below horizontal.**
- **Horizontal Intensity (H) defines the horizontal component of the total field intensity.**
- **Vertical Intensity(Z) defines the vertical component of the total field intensity.**
- **Total Intensity (F) is the strength of the magnetic field, not divided into its component parts.**



$$H = \sqrt{X^2 + Y^2} \tag{1}$$

$$X = H \cos D \tag{2}$$

$$Y = H \sin D \tag{3}$$

$$F = \sqrt{X^2 + Y^2 + Z^2} = \sqrt{H^2 + Z^2} \tag{4}$$

$$D = \tan^{-1}\left(\frac{Y}{X}\right) \tag{5}$$

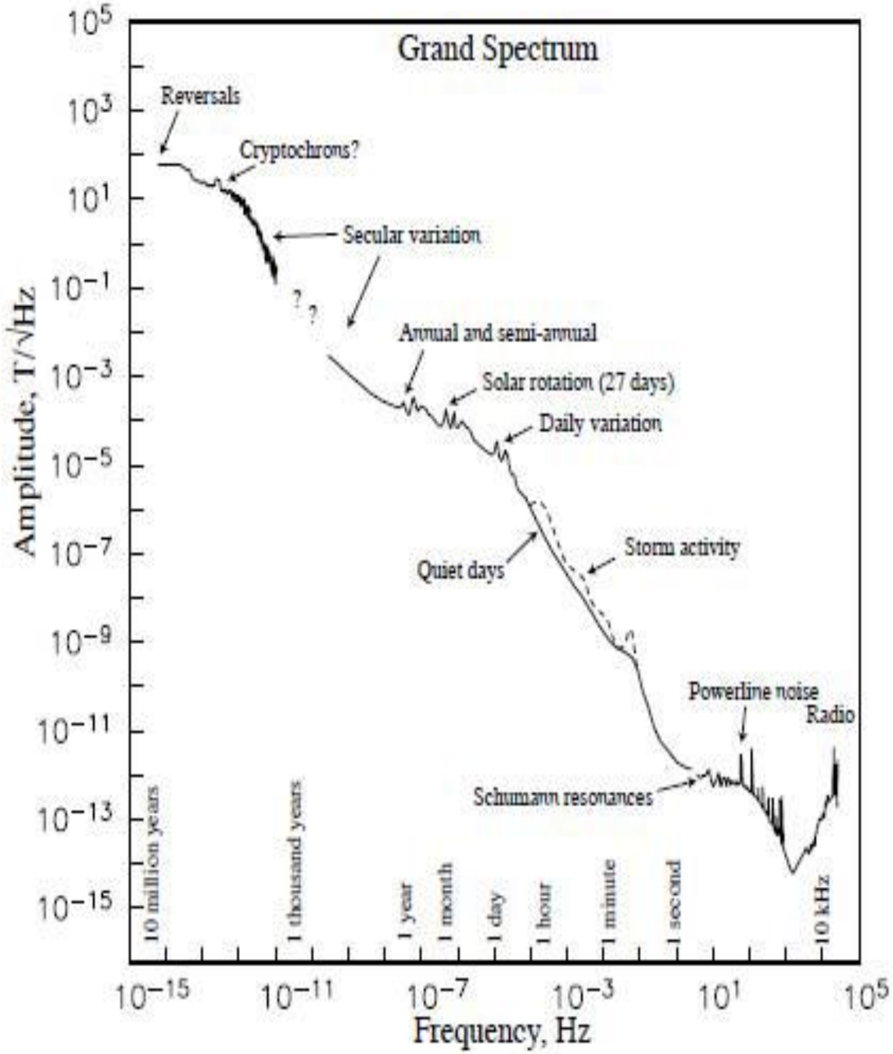
$$D(nT) = H\tan(D^{O}) \tag{6}$$

- On occasion, the declination angle D in degrees (D◦) is expressed in magnetic eastward directed field strength D (nT) and obtained from the relationship.

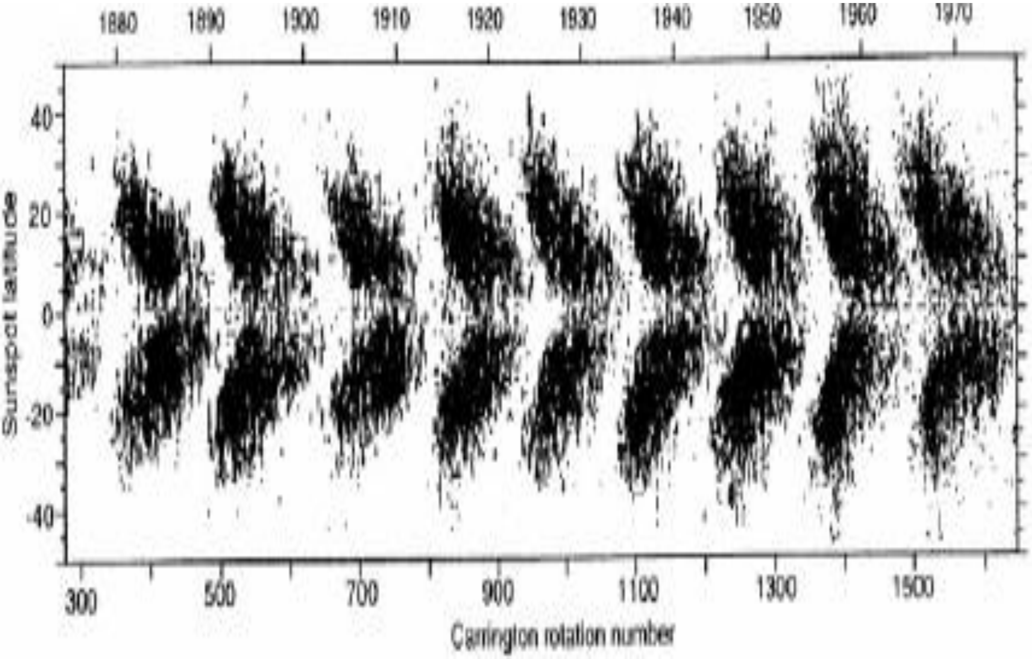
- Sometimes the change of D (nT) about its mean is called a magnetic eastward field strength, E. (For small, incremental changes in a value it is the custom to use the symbol)

Geomagnetic Variation

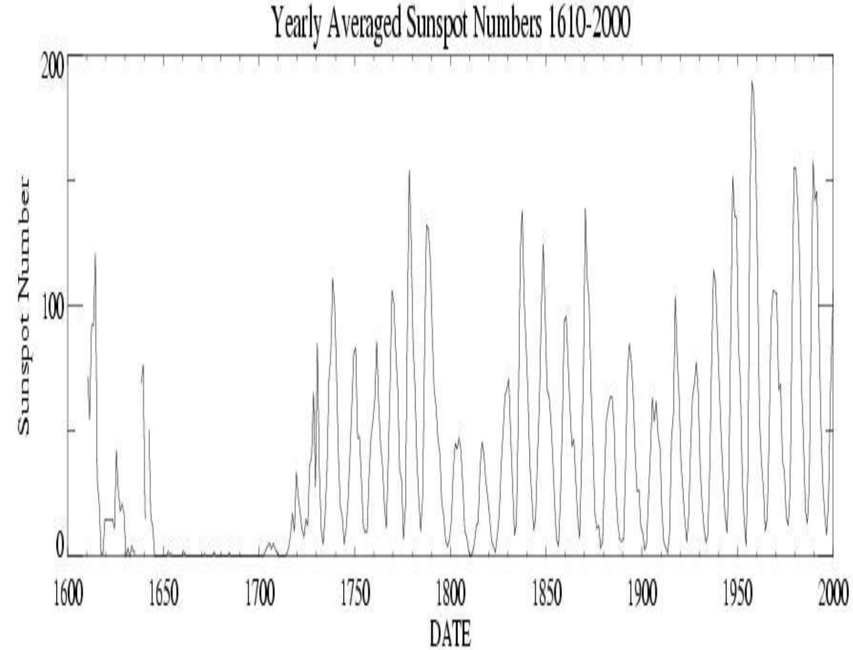
- ❑ **Solar variations**
- ▪ 11-year variation
- ▪ annual variation
- ▪ 27-day variation
- ▪ daily change (Sq)
- ❑ **Solar Wind-Magnetosphere Interaction**
- ▪ magnetic storm
- ▪ auroral substorms
- ▪ DP2, sfe,



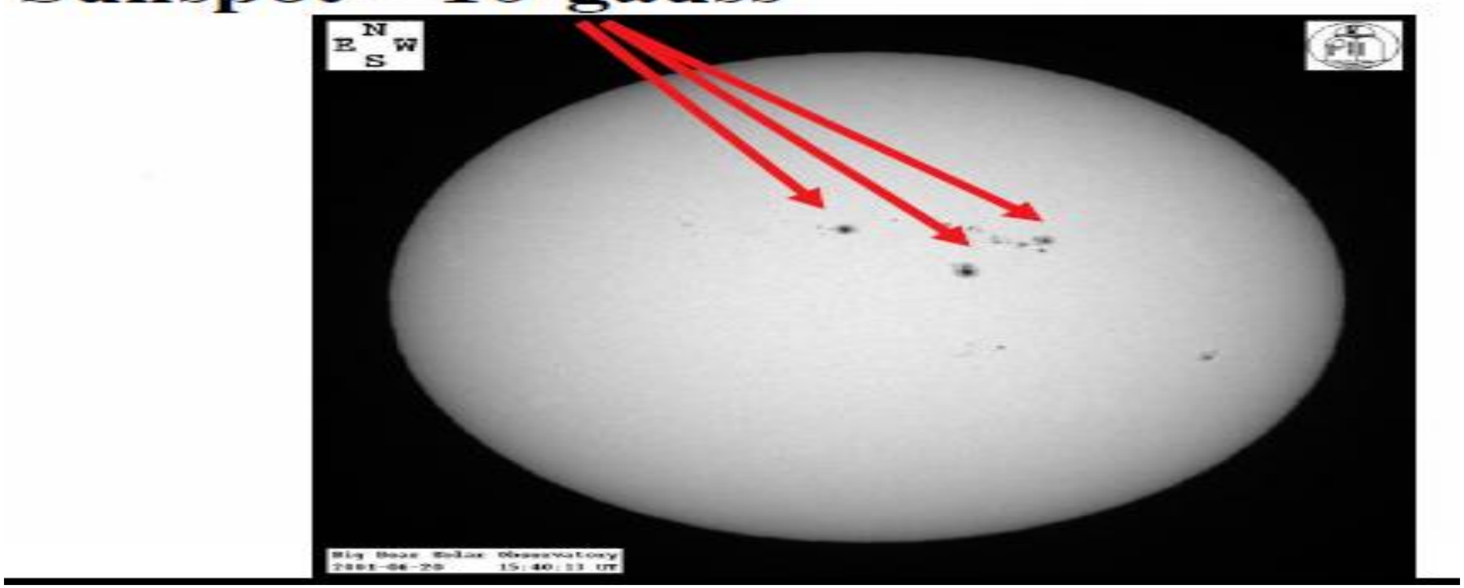
11 yrs variation of sunspot



11-year Variation of Sunspot Number

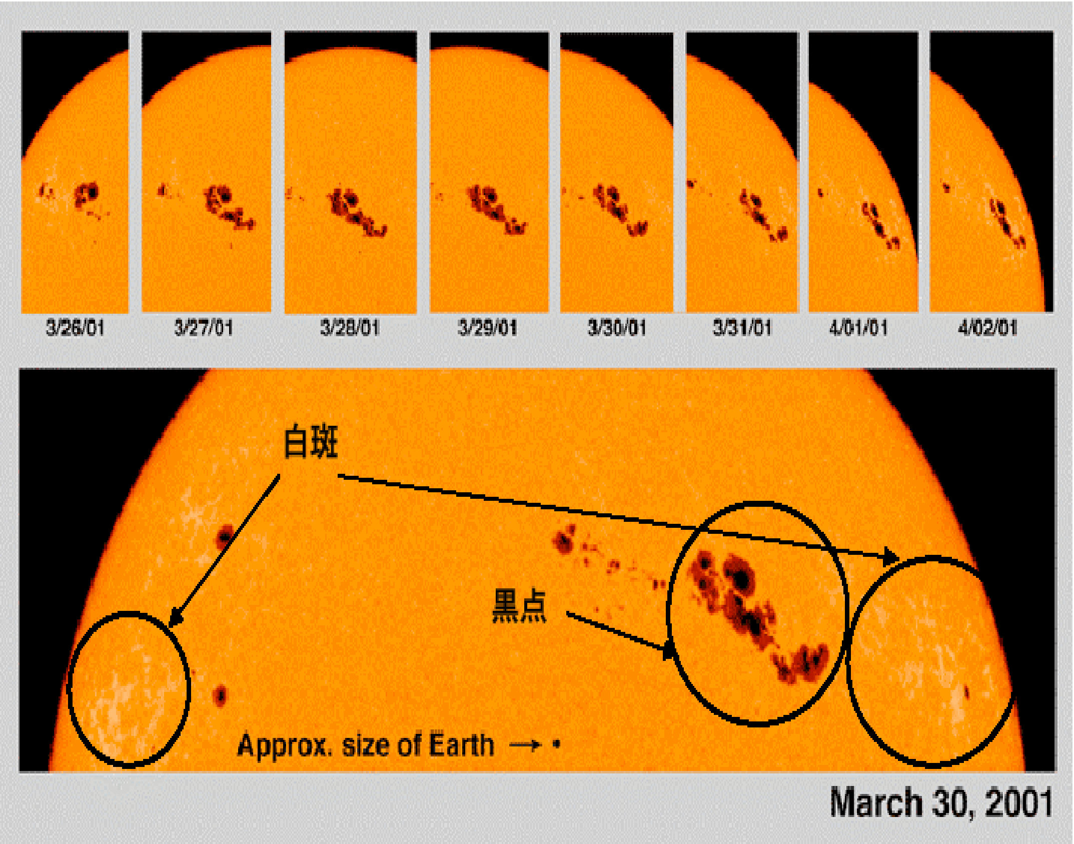


Sunspot～10^3gauss

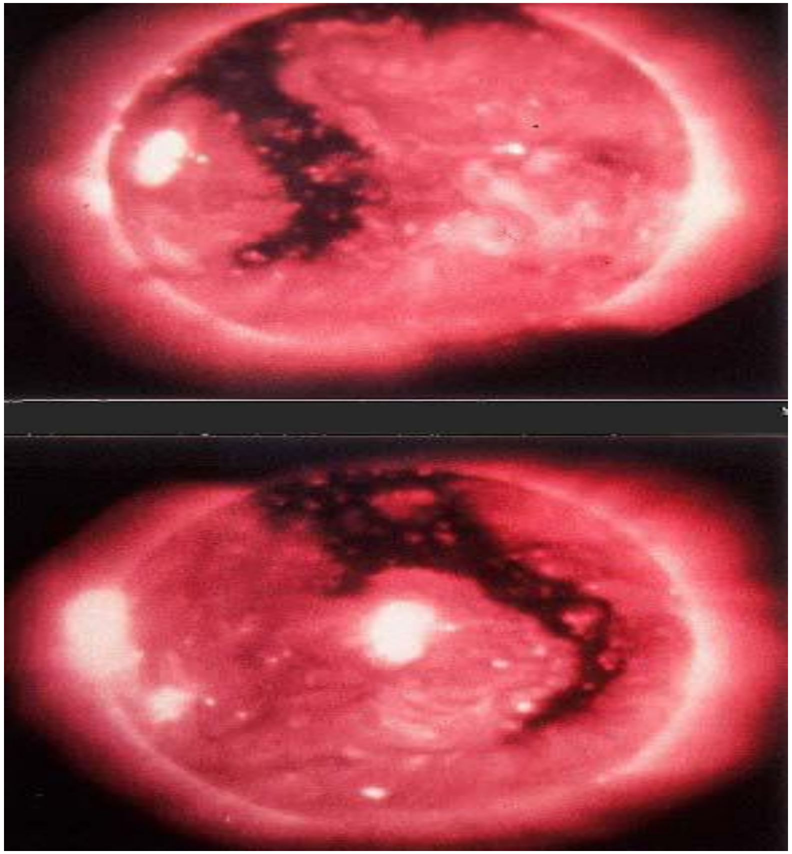


27-day Kp variation related with the solar rotation

Rotation of Sunspot (active region)



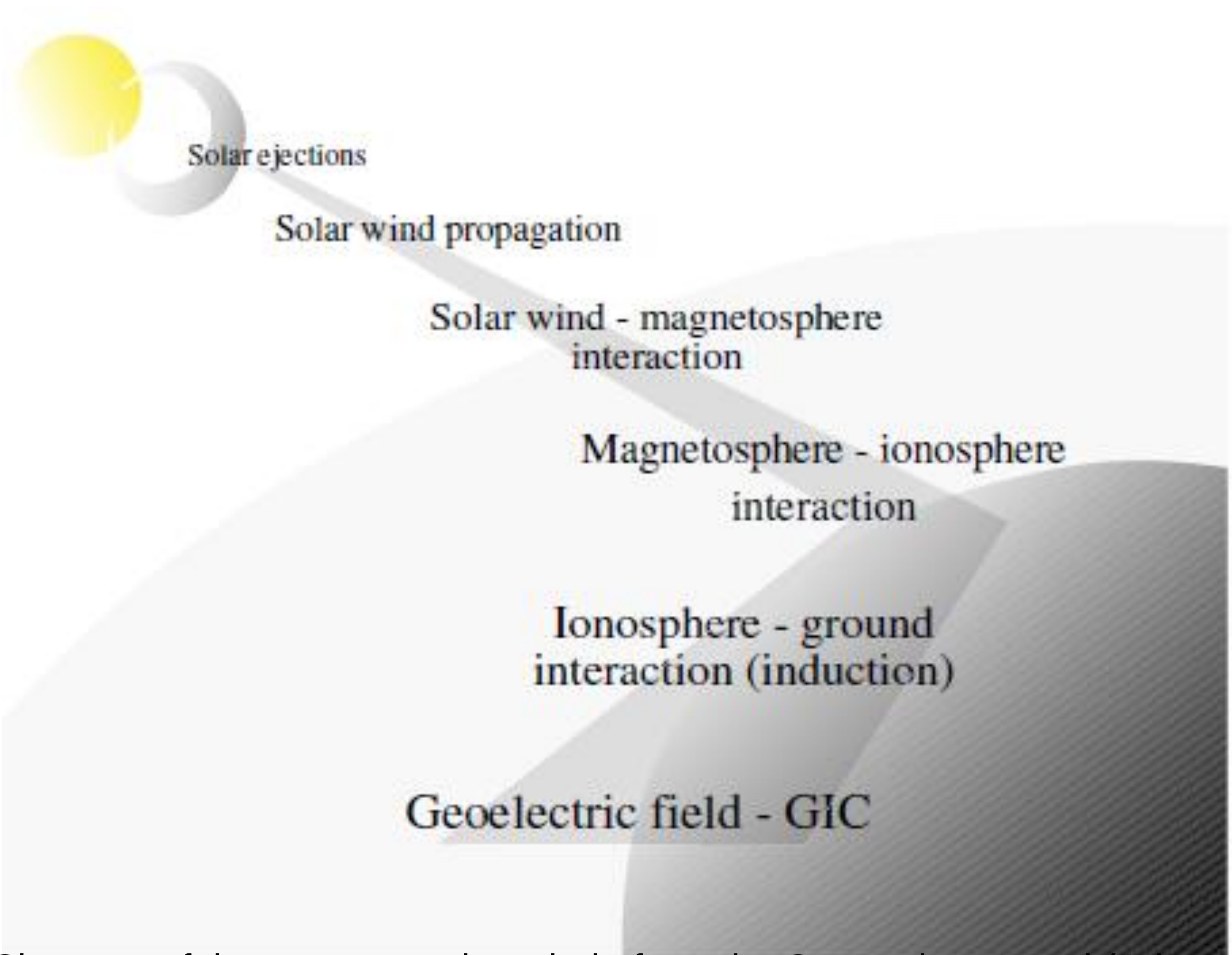
Rotation of Coronal Hole (High Velocity Stream)



The Sun is the source of the solar wind disturbances that drive geomagnetic activity and thus it seems that solar activity should predict geomagnetic activity.

Solar eruptions such as flares, filament eruptions and coronal mass ejections are active producers of geomagnetic activity. The frequency of these eruptions rises and falls with the solar activity cycle as indicated by the number of sunspots.

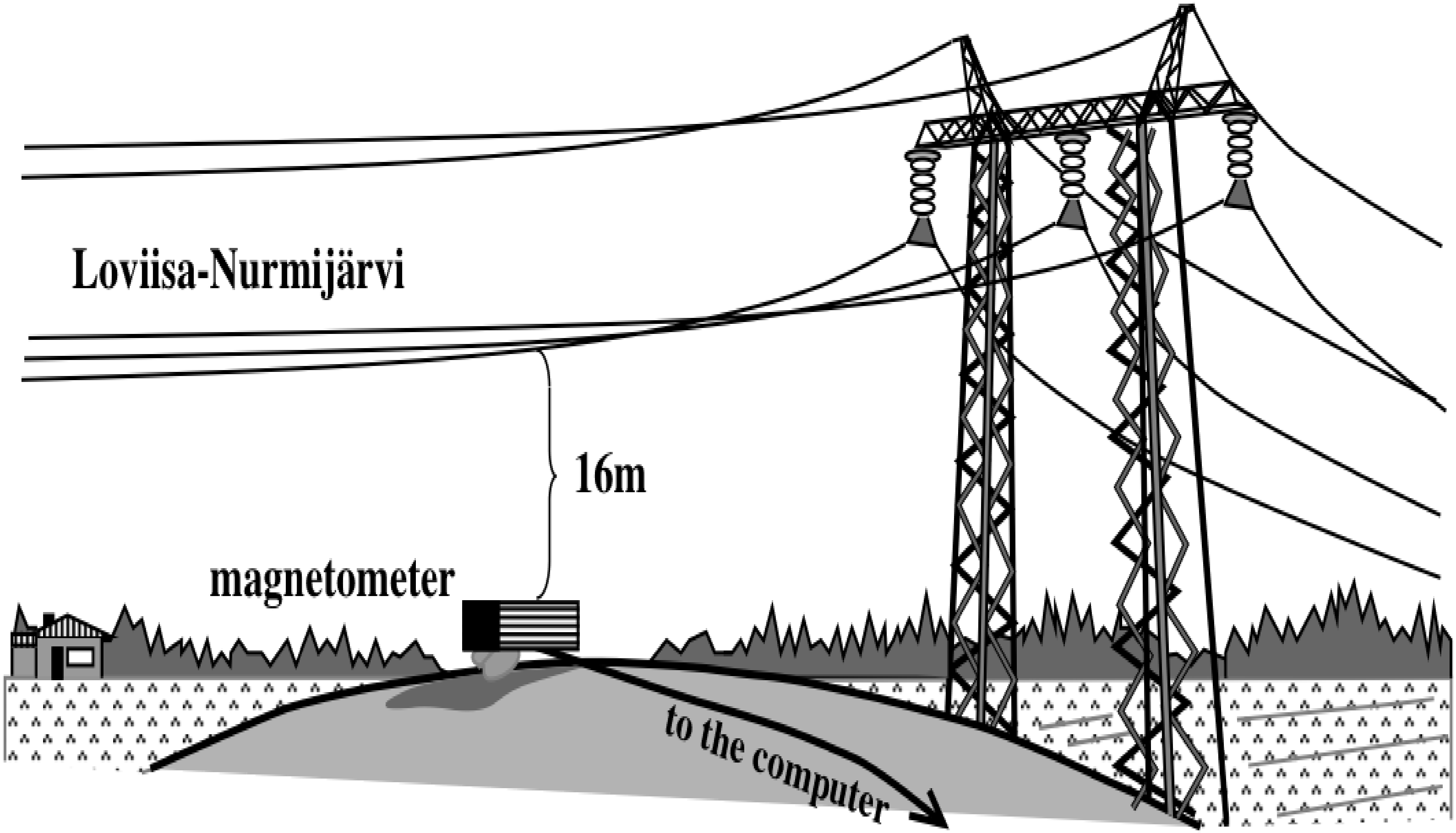
The sunspot number could be used to estimate the state of geomagnetic activity in the declining and maximum phase of solar activity during intervals when geomagnetic measures were not available (Rangarajan and Barreto ,1999)



Six steps of the space weather chain from the Sun to the ground (Adopted from Antti Pulkkinen, 2003)

How are power systems affected?

- In power transmission systems, electrical lines are connected to the Earth through transformers.
- The geomagnetically induced currents flow through the transformer windings at transformer substations, producing extra magnetization that can saturate the core of the transformer.
- This results in overheating of the transformer and the malfunctioning of relays and other equipment in the system.



Measurement of GIC flowing in a power transmission line by using a magnetometer below the line and another magnetometer for reference data further away (Viljanen et al., 2009)

How are pipelines affected?

- To prevent corrosion, steel pipelines are covered with an isolating coating and, using corrosion protection rectifiers, kept within a safe range of voltages that minimizes the corrosion process.
- Geomagnetic variations create voltage swings that take the pipeline voltage out of that safe ‘protected' range.
- During geomagnetic storms, these variations can be large enough to keep portions of a pipeline in the unprotected regime for some time. This effect is cumulative and can result in increased corrosion and a significant reduction in the lifetime of the pipeline

Modelling of GIC

- 1. Determination of the horizontal geoelectric field at the Earth's surface (*"geophysical part").*
- 2. Computation of GIC in the network produced by the geoelectric field (*"engineering part").*
- The geophysical part does not depend on the particular network and is thus the same for power networks, pipelines and other conductor systems. The input of the geophysical part consists of knowledge or assumptions about the Earth's conductivity and about the magnetospheric-ionospheric currents or about the geomagnetic variations at the Earth's surface. The solution is based on Maxwell's equations

- One of the key concepts in geomagnetic induction is that of the skin depth, the characteristic length over which electromagnetic fields attenuate. We can derive the skin depth starting with

Faraday's law

$$\nabla \times E = -\frac{dB}{dt} \qquad (1)$$

Ampere's law

$$\nabla \times H = -J \qquad (2)$$

where J is the current density (A m $^{-2}$), E is the electric field (V m^{-1}), B is the magnetic flux density or induction (T), and H is the magnetic field intensity (A m $^{-1}$). We neglect displacement currents, as they are not significant at the frequencies and conductivities relevant to geomagnetic induction

We can use identity $\nabla \bullet \nabla \times A = 0$

$$\nabla \times B = 0 \qquad (3)$$

$$\nabla \times J = 0 \qquad (4)$$

in regions free of sources of magnetic fields and currents. B and H are related by magnetic permeability m and J and E by conductivity σ

$$B=\mu H \qquad (5)$$

$$J= \sigma E \qquad (6)$$

(the latter equation is Ohm's law), and so

$$\nabla \times E = -\mu \frac{dH}{dt} \qquad (7)$$

$$\nabla \times H = \sigma E \qquad (8)$$

If we take the curl of these equations and use

$$\nabla \times (\nabla \times A) = \nabla(\nabla \bullet A) - \nabla^2 A \qquad (9)$$

for constants σ and μ , we have

$$\nabla^2 E = \mu \frac{d}{dt}(\nabla \times H) = \mu\sigma \frac{dE}{dt} \qquad (10)$$

$$\nabla^2 H = \sigma(\nabla \times E) = \mu\sigma \frac{dH}{dt} \qquad (11)$$

which are diffusion equations. In air and very poor conductors where σ =0, or if w=0, the equations reduce to Laplace's equation. Now, if we consider sinusoidally varying fields of angular frequency **w,**

$$E(t) = E_o e^{iwt} \qquad \frac{dE}{dt} = iwE \qquad (12)$$

$$H(t) = H_o e^{iwt} \qquad \frac{dH}{dt} = iwH \qquad (13)$$

and so

$$\nabla^2 E = iw\mu\sigma E \qquad (14)$$

$$\nabla^2 H = iw\mu\sigma H \qquad (15)$$

If we further consider fields that are horizontally polarized in the xy directions and are propagating vertically into a half space, in Cartesian coordinates, these equations decouple to

$$\frac{d^2E}{dz^2} + k^2E = 0 \quad (16)$$

$$\frac{d^2H}{dz^2} + k^2H = 0 \quad (17)$$

with solutions

$$E = E_o e^{-ikz} = E_o e^{i\alpha z} e^{-\beta z} \quad (18)$$

$$H = H_o e^{-ikz} = H_o e^{i\alpha z} e^{-\beta z} \quad (19)$$

where we have defined a complex wave number

$$k = \sqrt{iw\mu\sigma} = \sigma - i\beta \quad (20)$$

and an attenuation factor, which is called a skin depth,

- The magnetic field variations induce electric currents in the earth which also produce magnetic fields that contribute to the magnetic disturbances observed at the earth's surface. Inside the earth, the induced currents act to cancel external magnetic field variations leading to a decrease of the currents and fields with depth. At low frequencies, the skin depth δ is characterized by

$$\delta = \sqrt{\frac{2}{\sigma \mu_o w}} \tag{21}$$

The geoelectric field model

- The induced electric field observed at the Earth's surface depends primarily on the magnetospheric-ionospheric currents, which in turn are dependent on space weather conditions, while the secondary effects are determined by the conductivity structure of the Earth (Pirjola, 2000).

- Pirjola (2002b) explains that the horizontal geoelectric field at the surface of the Earth is an important quantity that must be known in order to determine the magnitude of the GIC in the network.

- Different techniques and models for performing the geophysical part have been investigated for a long time (e.g. Pirjola, 2002, and references therein).

- An interesting approximate alternative is the Complex Image Method (CIM), in which the currents induced in the conducting Earth are replaced by images of ionospheric currents located in a complex space (Boteler & Pirjola, 1998; Pirjola and Viljanen, 1998).

- A crucial parameter in CIM is the complex skin depth p = p(w), which depends on the angular frequency w considered (i.e. We assume a harmonic dependence on the time t given by exp(iw$t$))

- $$p(w) = \frac{Z(w)}{iw\mu_o} \qquad (22)$$

- where $Z = Z(w)$ is the surface impedance at the Earth's surface relating a horizontal electric field component $Ey = Ey(w)$ to the perpendicular horizontal magnetic field component $Bx = Bx(w)$ (see e.g. Kaufman & Keller, 1981; Pirjola et al., 2009).

- $$E_y(w) = -\frac{Z(W)}{\mu_o} B_x w \qquad (23)$$

- It is implicitly required in equation (23) that the (flat) Earth surface is the *xy plane of a right handed* Cartesian coordinate system in which the *z axis points downwards. In practice, the* surface impedance included in equation (23) and especially in equation (22) refers to the plane wave

- The geoelectric field at the Earth's surface can be modeled using the plane wave model (Viljanen and Pirjola, 1989; Pirjola, 2002c).

- Let us assume now that the Earth is uniform with the conductivity σ and consider a harmonic time dependence with the angular frequency w. It is easy to show that the horizontal geoelectric field component *Ey = Ey(w) at the Earth's surface is related to the* perpendicular horizontal geomagnetic variation component *Bx = Bx(w) by the following* equation (e.g. Pirjola, 1982)

$$E_y = -\sqrt{\frac{w}{\mu_o \sigma}} e^{\frac{i\pi}{4}} B_x \qquad (24)$$

- Equation (24) shows that there is a 45-degree (π/4-radian) phase shift between the geoelectric and geomagnetic fields. We also see that an increase of the angular frequency and a decrease of the Earth's conductivity enhance the geoelectric field with respect to the geomagnetic field.

- Noting that $iwB_x(w)$ *is associated with the time derivative of* $B_x(t)$ *, equation (24) can be* inverse-Fourier transformed to give the following time domain convolution integral (Cagniard, 1953; Pirjola, 1982)

- This equation shows that the magnitude of the geoelectric field increases with increasing frequency and an inverse Earth conductivity. Eqn. (24) can be transformed from the frequency (ω) domain to a time (t) domain by carrying out an inverse-Fourier Transform (Pirjola, 2002c) to obtain

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_o\sigma}}\int_0^{\alpha}\frac{g(t-u)}{\sqrt{u}}du \qquad (25)$$

where the time derivative of *Bx*(*t*) is denoted by *g*(*t*). Equation (24) is in agreement with the Ey(t) at the time t only depends on earlier values of g(t). The square root of the lag time *u* in the denominator means that the influence of a value of *g*(*t-u*) on *Ey*(*t*) decreases with increasing *u* or as above in equation (24).

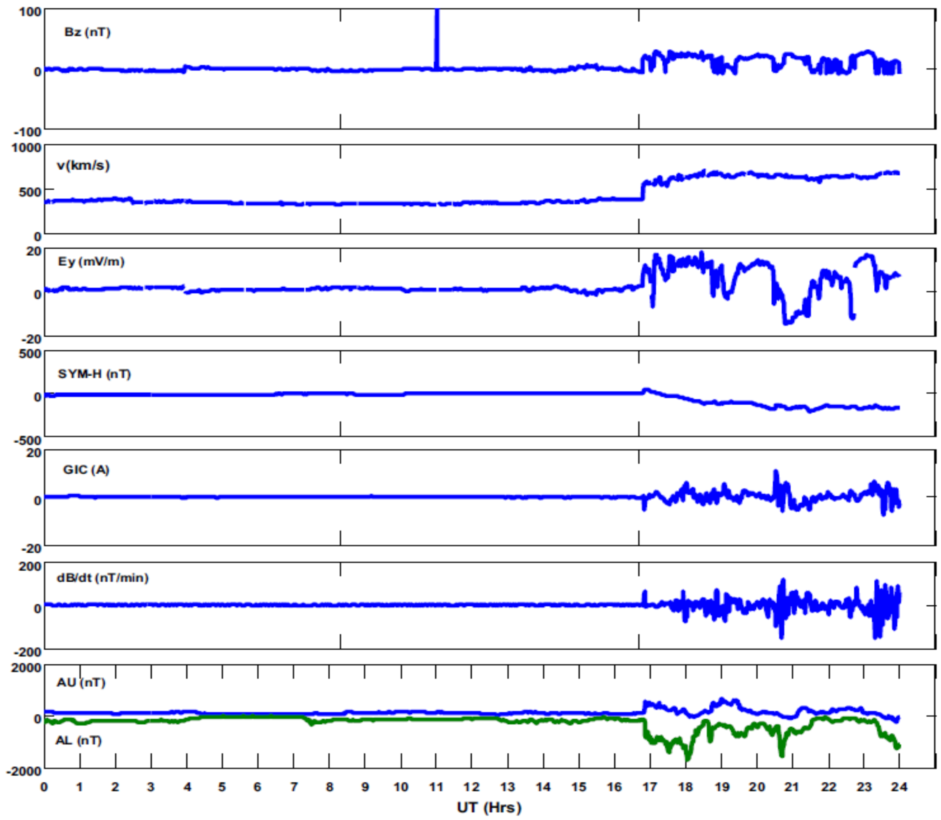
- A regression analysis was performed to test the relationship between geoelectric field and GIC on different days of the events. This had the form

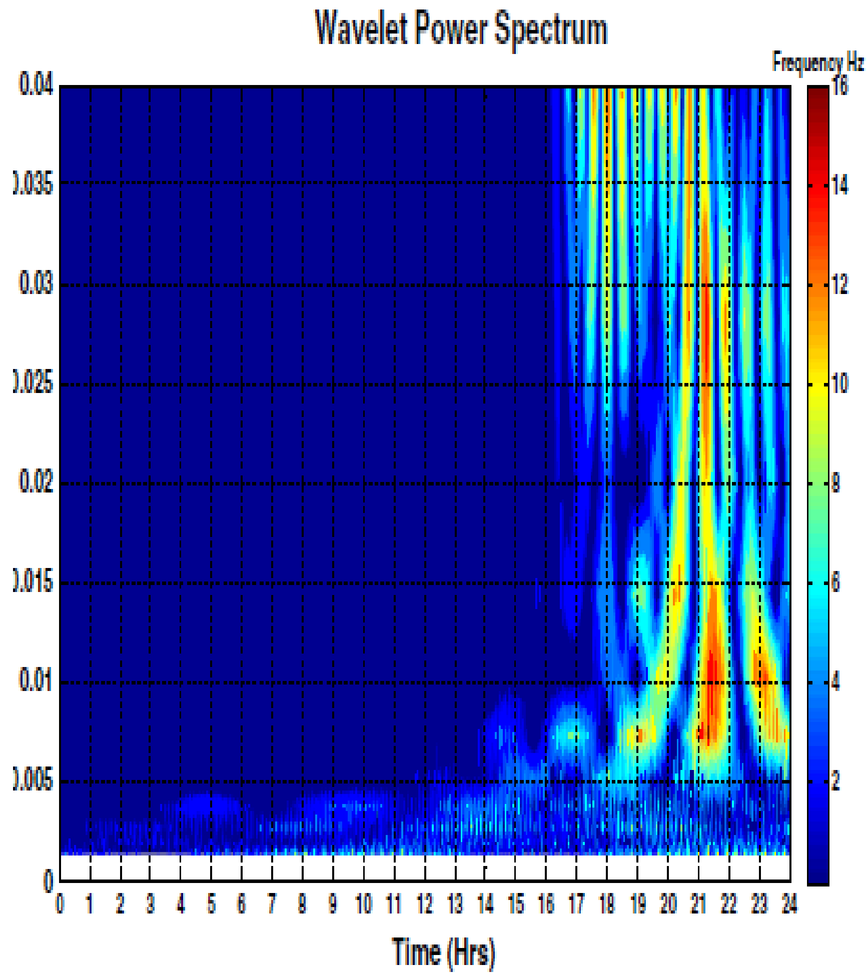
$$GIC = aE_x + bE_y \qquad (25)$$

- GICs can be modeled by the equation (25). Where the GIC and electric field are local (site specific) and the coefficients a and b are specific to each transformer and power line. The coefficients a and b depend only on the resistances and configuration of the power system [Viljanen and Pirjola, 1994].

Date of Events	a	b	r	R^2	RMSE
20000918	-2.396	0.063	0.927	0.860	0.445
20010331	1.369	0.081	0.849	0.721	0.721
20011021	1.376	0.055	0.906	0.821	0.304
20011106	1.738	0.026	0.866	0.750	0.910
20011124	-1.512	0.029	0.872	0.760	0.358
20031029	9.253	0.026	0.922	0.850	0.312
20031031	0.449	0.019	0.970	0.941	0.469
20041109	1.837	0.017	0.880	0.774	0.416

Falayi and Beloff, 2013





Interplanetary parameters and geomagnetic parameters on 21 October 2001, Bz, v, Ey, SYM-H index, GIC, dB/dt, AU (blue line) and AL (green line) indices.

Wavelet spectrum analyses of the geomagnetic induced current on 21st October 2001

Falayi, et al., 2017

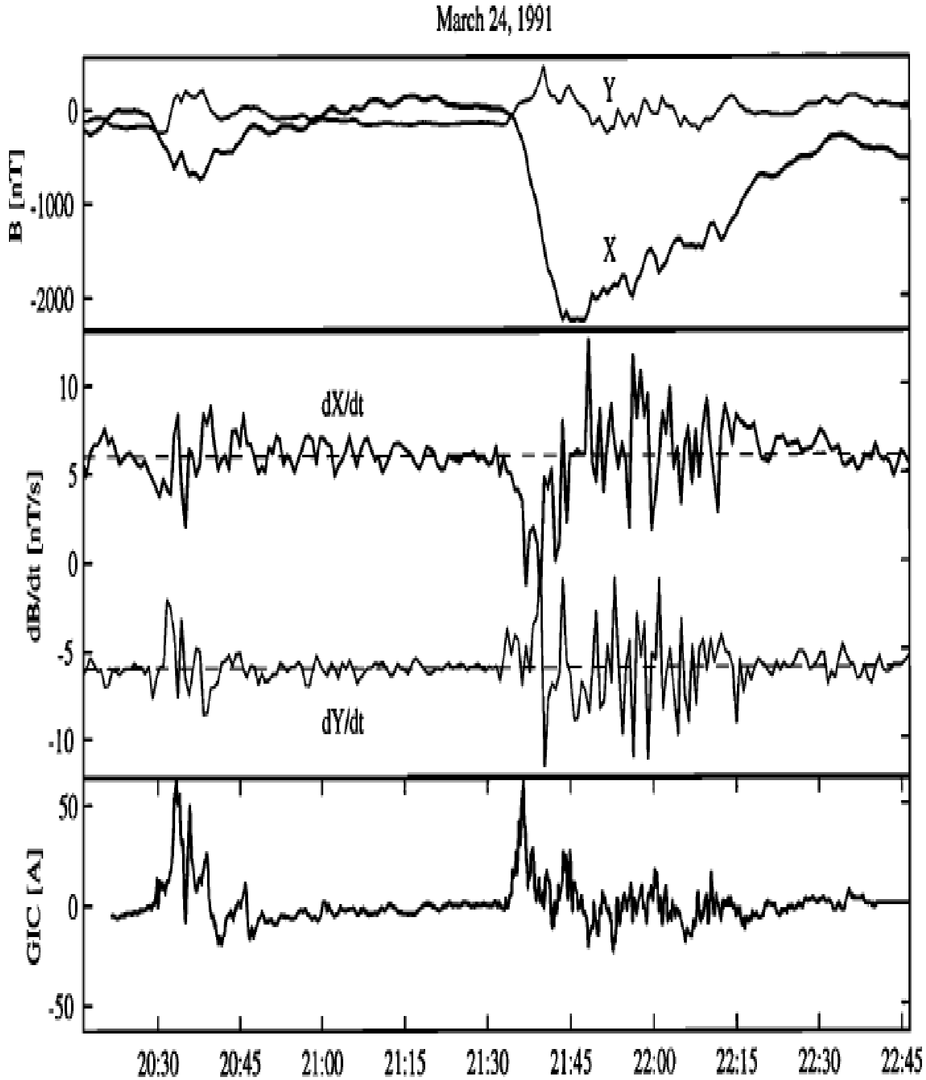
Variation of time derivatives of geomagnetic field

- Coles and Boteler (1993) and Boteler et al. (1997) studied the occurrence of large time derivatives of the magnetic field components when evaluating GIC risks in Canada.

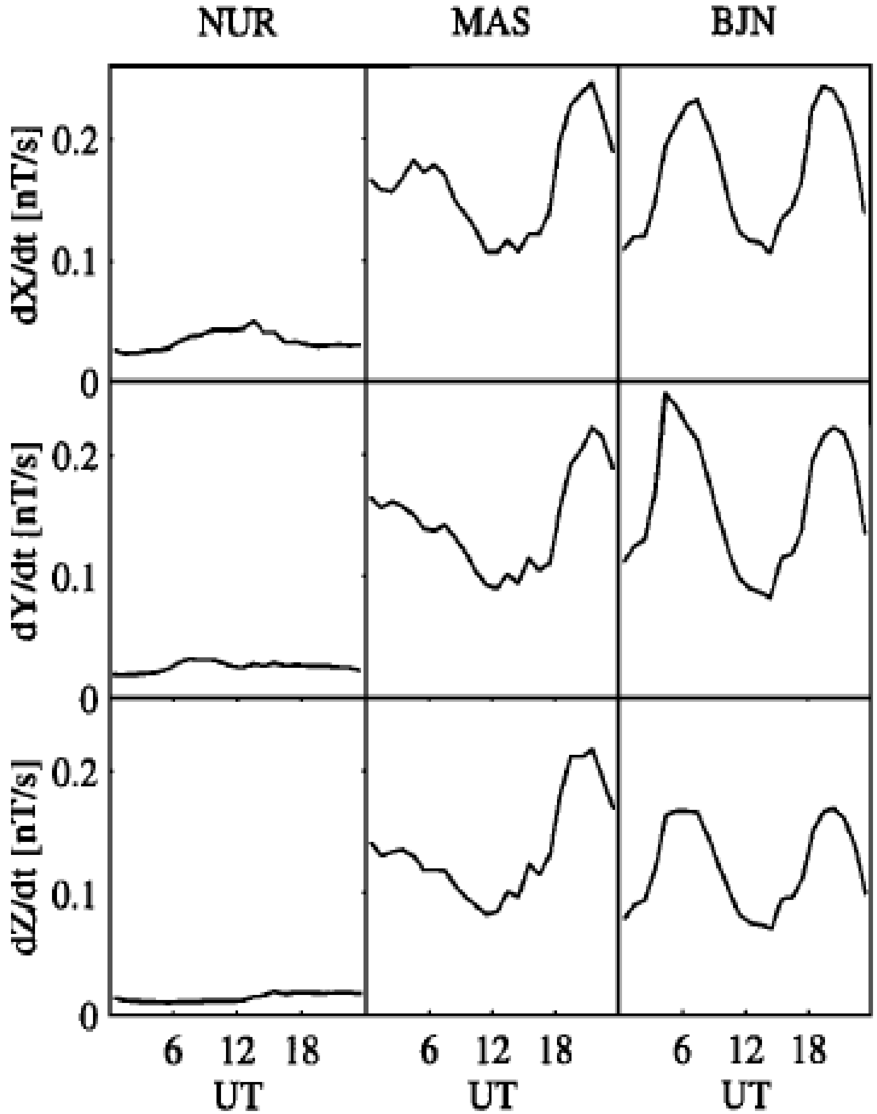
- GIC is closely related to the time derivative of the magnetic field (dB/dt), or more exactly, to its horizontal part (Coles et al., 1992; Makinen , 1993; Viljanen, 1998).

- Large GICs are always associated with large values of the time derivative of the geomagnetic field, and especially with its horizontal component (dH/dt).

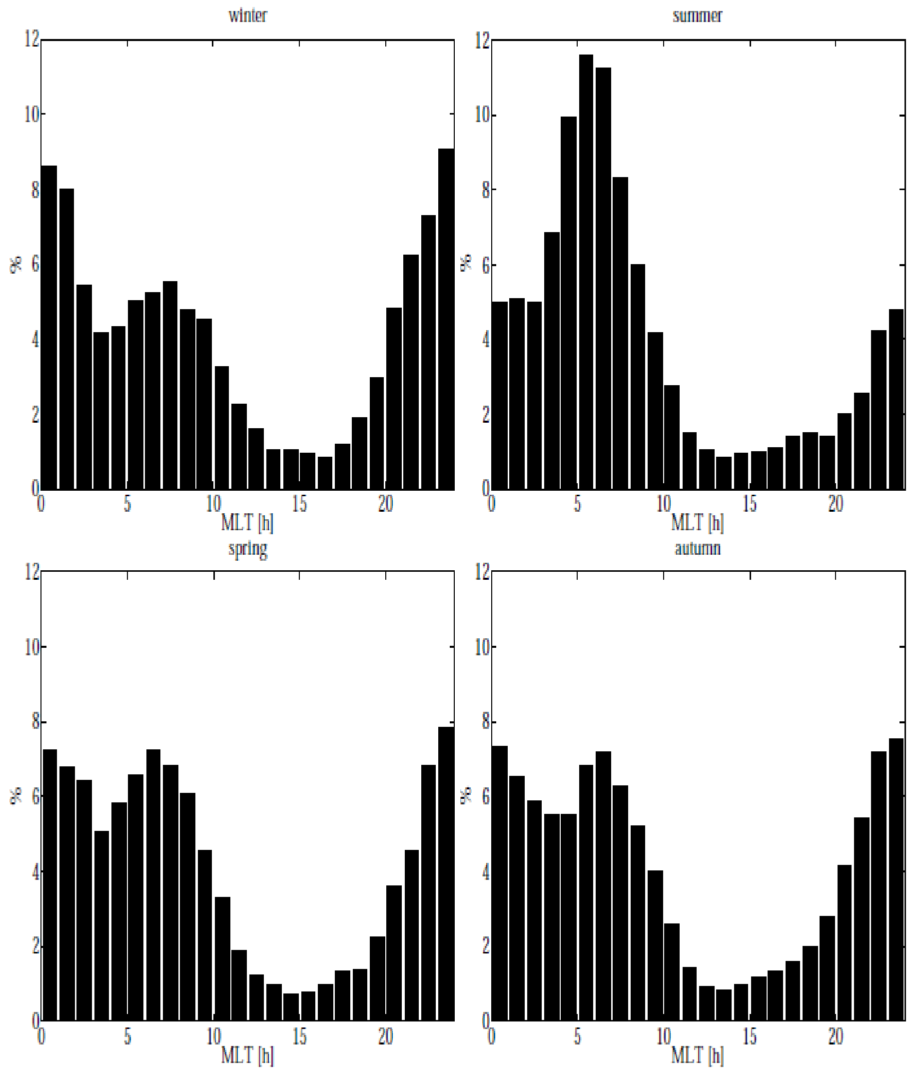
$$dH = \sqrt{(dB_X{}^2 / dt) + (dB_Y{}^2 / dt)} \qquad (26)$$



Top panel: X (thick line) and Y (thin line) at PEL on March2 4, 1991. The sampling interval is 20 s. Middle panel: dX/dt (thick line) and dY/dt (thin line). Zero levels are plotted with dashed line. Bottom panel: Geomagnetically induced current Pirttikoski 400kV transformer positive current flows (Viljanen, 1997)

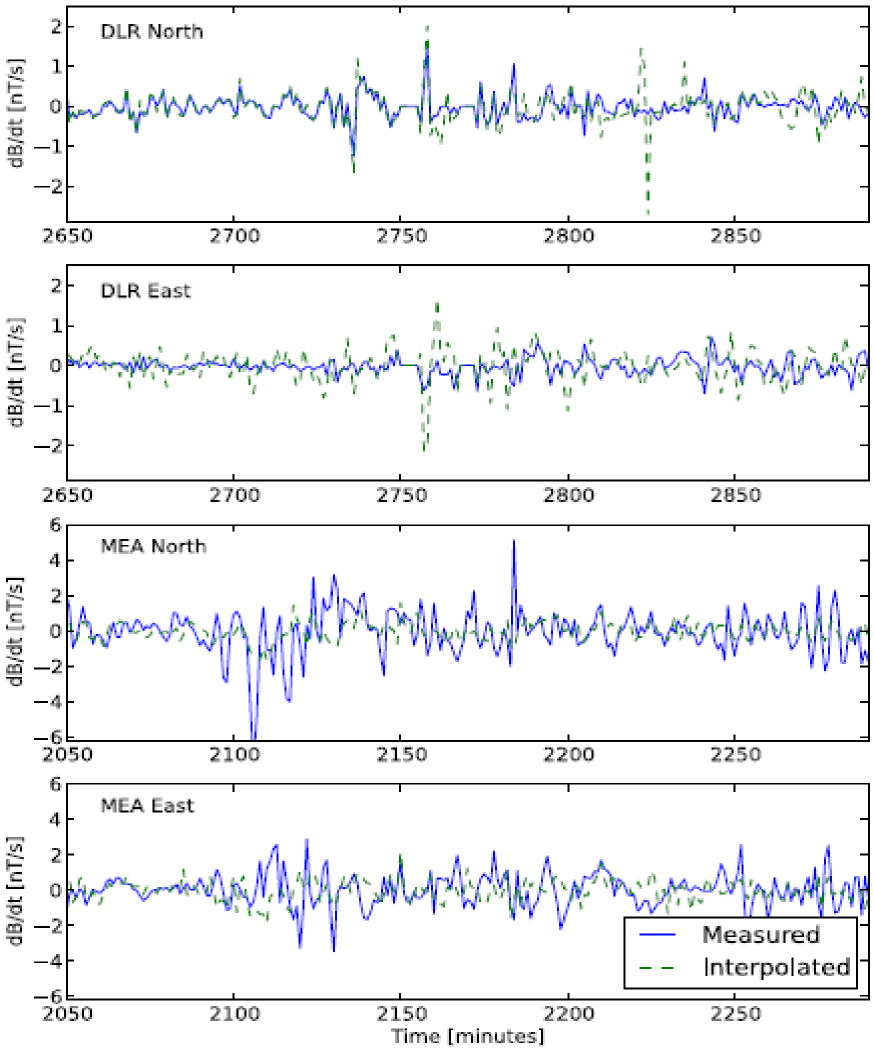


Average diurnal time derivative of the magnetic field at NUR,MAS, BJN during the 157 days samples (Viljanen, 1997)

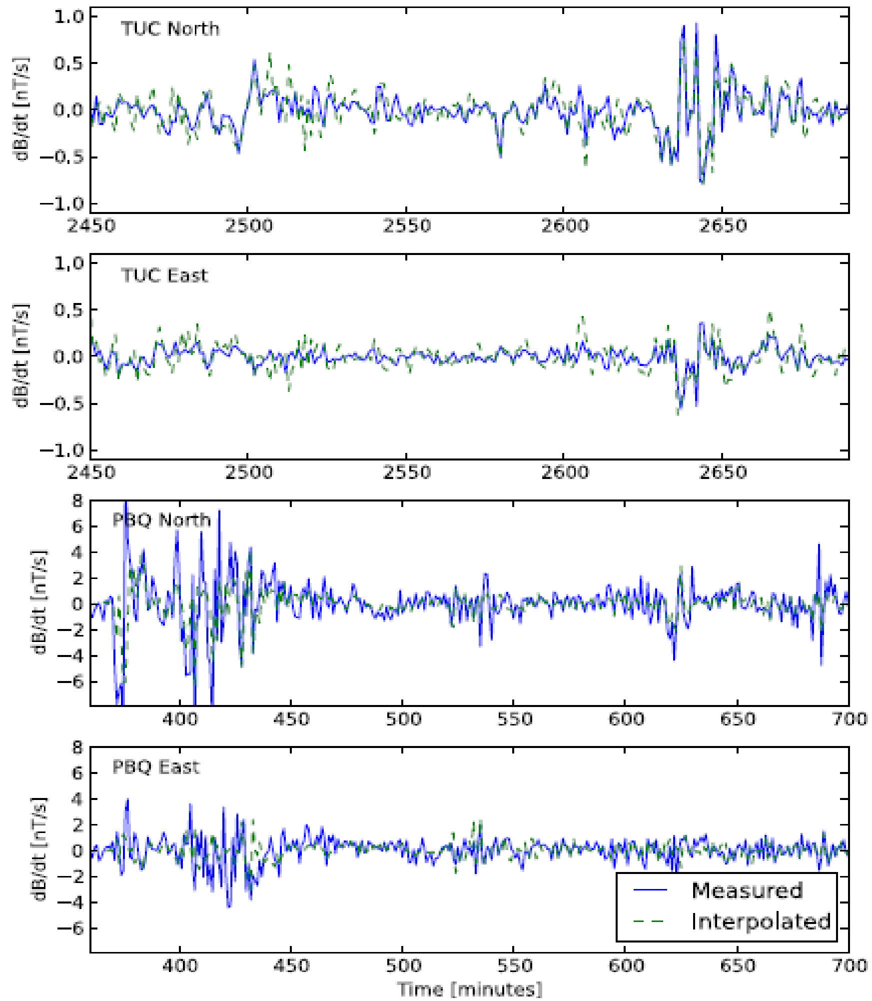


Average diurnal occurrence of dH/dt exceeding 1 nT/ s at five stations in northern Europe (Table 1) over the solar cycles 22–23 in 1986–2009 during different seasons (Viljanen and Tanskanen, 2011).

- The diurnal occurrence of large dH/dt during different seasons .
- Spring and autumn are again very similar to each other: the midnight and morning maxima are equally large.
- The difference between winter and summer is clear: it is most likely to have large dH/dt around midnight in winter, whereas the morning time is strongly preferred in summer.



Comparison of the measured (solid blue lines) and interpolated (dashed green lines) magnetic field time derivatives for the 1989 "Quebec" storm for the station with the lowest (DLR) and highest (MEA). Missing magnetic field data are set to zero. Note that the magnetic field data are separated by 1 min intervals but divided by 60 s to determine d*B/dt. (Wei et al., 2013)*



Comparison of the measured (solid blue lines) and interpolated (dashed green lines) magnetic field time derivatives for the 2003 "Halloween" storm for the station with the lowest (TUC) and highest (PBQ) . Missing magnetic field data are set to zero. Note that the magnetic field data are separated by 1 min intervals but divided by 60 s to determine d*B/dt. (Wei et al., 2013)*

Recommendation for Power Failure

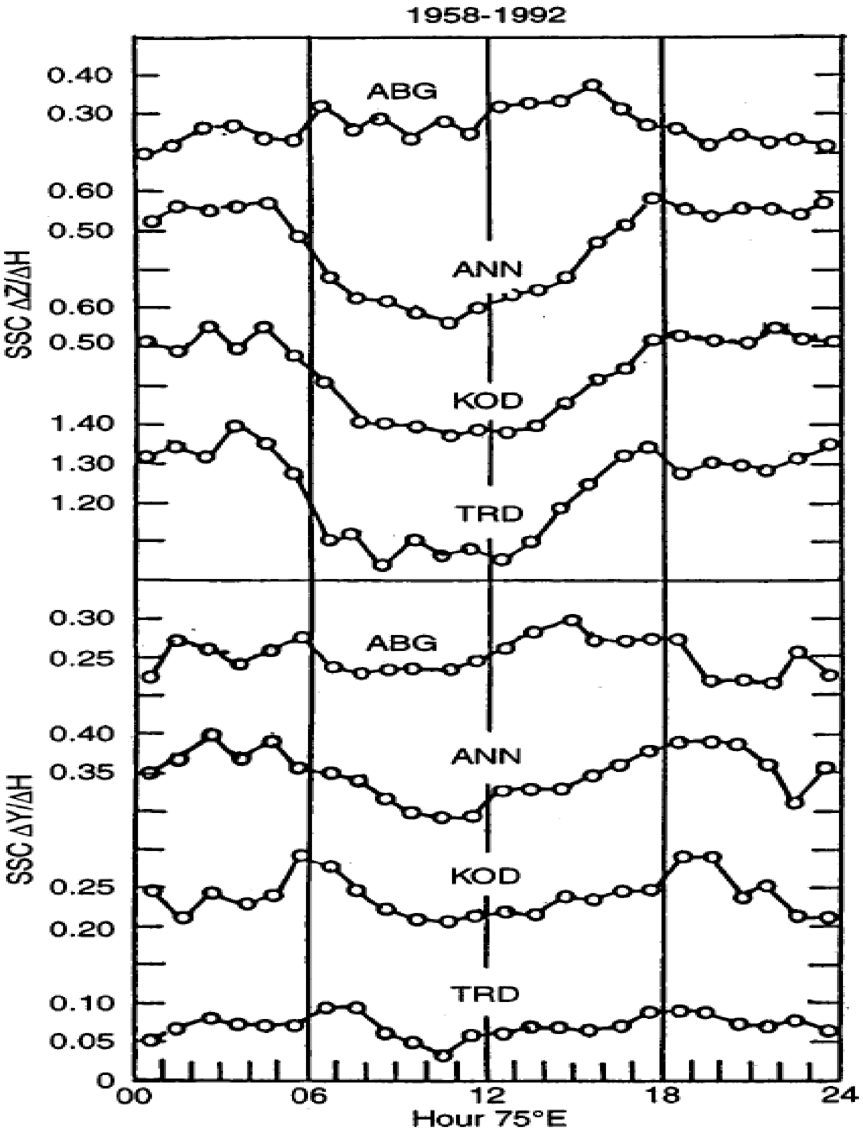
- Ground based technology are prone to GIC when oriented east-west, rather than north-south. The ionospheric response is associated with geomagnetic disturbance which usually flows in an east west direction including GIC.
- According to Pirjola (2002) implementation of series capacitors in transmission lines or in the earthling wires of transformer are readily available technology that can be used to block GIC

- Interconnectedness should be discourage because it increases vulnerability. When a geomagnetic storm damages one piece of equipment, another connected to the affected system can also experience power failure.
- During geomagnetic disturbance and when electrical power grids are highly loaded, increased power demand from customer and industry led to the system operating closer to their limit or above their limit making susceptible to external disturbance
- Measuring and monitoring of ground based technology especially at site vulnerable to GIC.

Variations of electromagnetic induction (dZ/dH) during geomagnetic disturbance

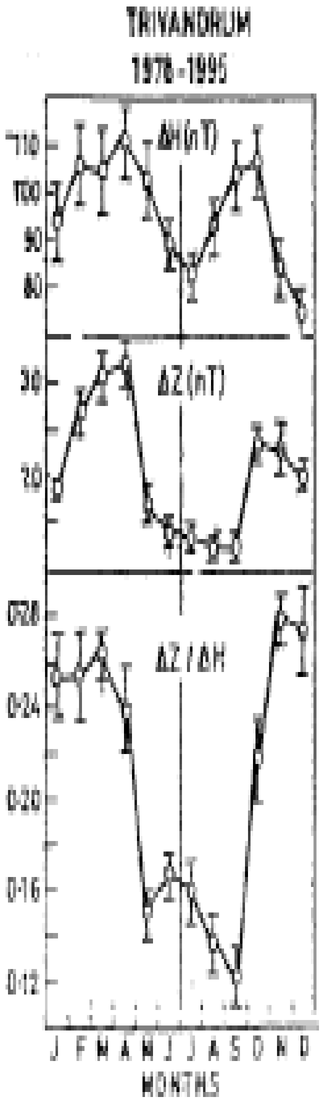
- Magnetotellurics and geomagnetic depth sounding are the two major way of estimating the induced response of a laterally inhomogeneous sub surface, Tikhonov-Cagniard impedance expressing the relation between Electric E and magnetic H fields components forms the fundamental EM response function.
- described the inductive response of the electrically conducting Earth interior to geomagnetic variation that can be inferred from magnetic Z-H relation. Non uniformities in conductivity of the upper mantle produce local variation in Z-H relation.
- The geomagnetic field components Z (vertical field variation) and H (horizontal geomagnetic field) are used to map the lateral conductivity (Schmucker, 1970).

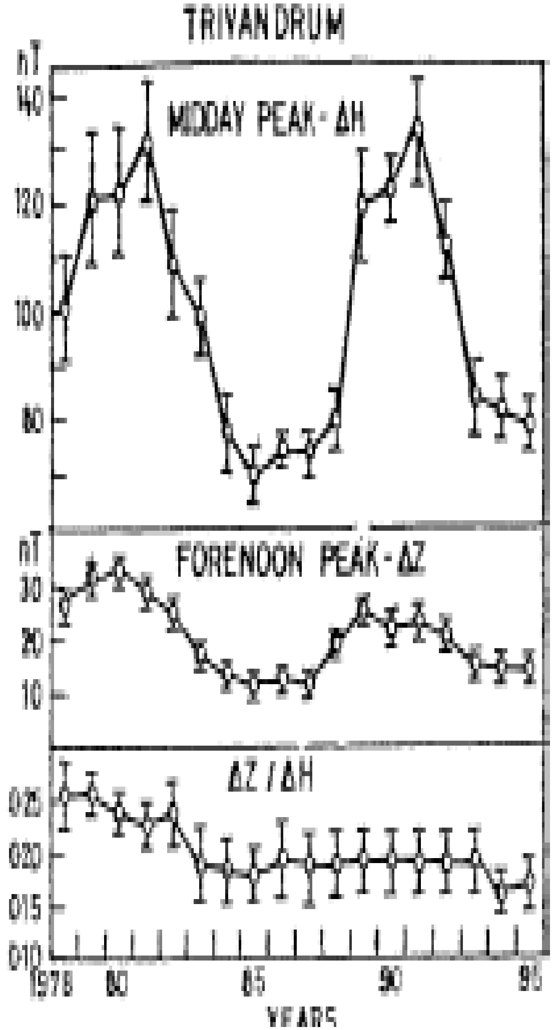
- Mayaud (1973) reported that the rate of induction due to electrojet can be determined by using the ratio $\Delta Z/\Delta H$ and asserted that such ratios are highly sensitive to the importance of the induced fields since internal effects are subtracted from the external effects in Z while they are added in H



Solar daily variations of the ratios of SSC amplitudes DY/DH and DZ/DH averaged over 1958-1992 at TRD, KOD,ANN and ABG (Rastogi, 1999)

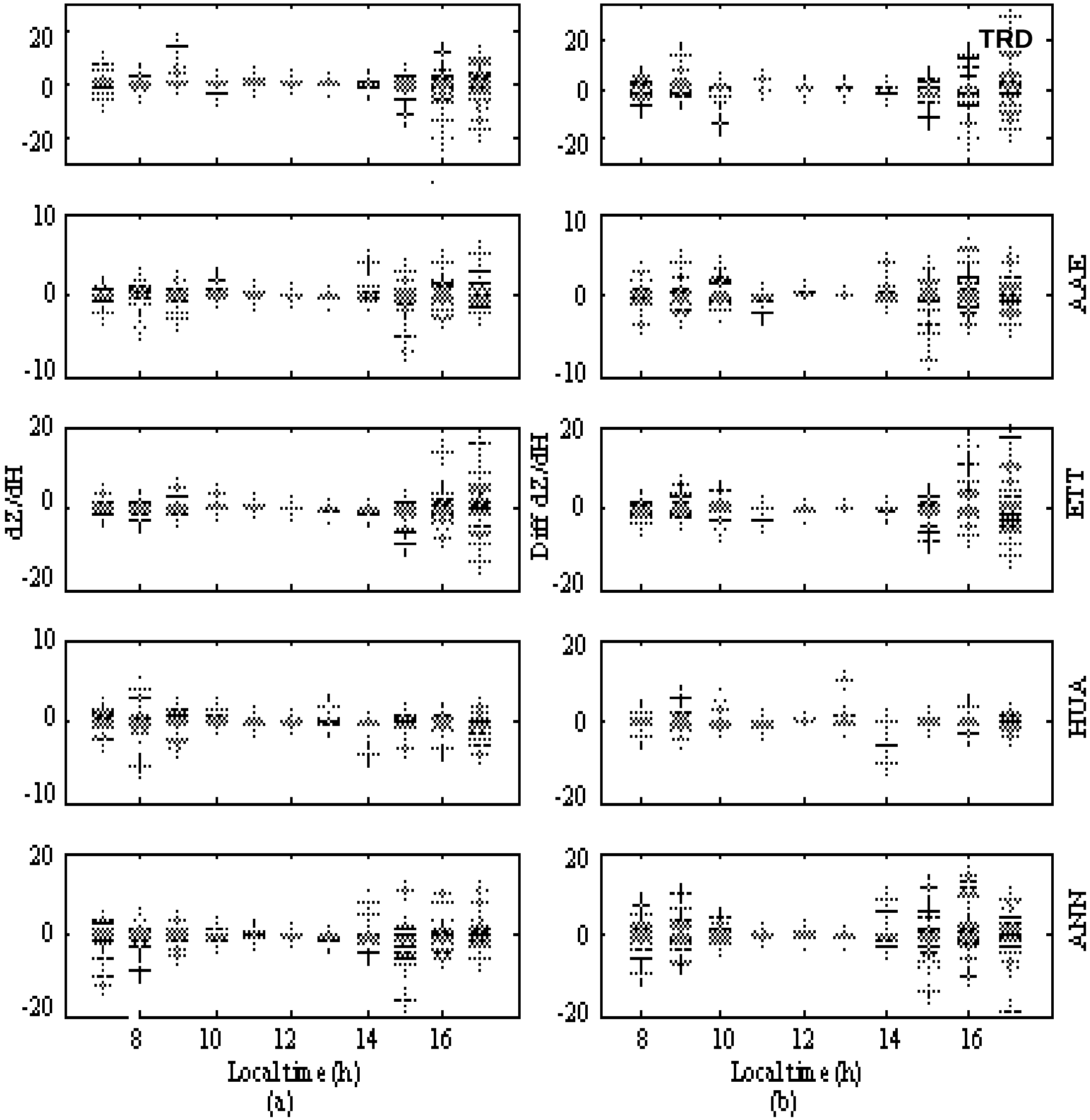
- Figure shows the diurnal variations of the ratios DY/DH and DZ/DH at each of the stations averaged over the entire period of study.
- The ratio DY/DH seems to have minor maxima at sunrise and sunset hours and a minimum around 10 00 LT.
- The value of DY/DH averaged over all hours of the day was 0.07 for TRD, 0.23 for KOD, 0.36 for ANN and 0.25 for ABG. It is to be noted that the ratio of DY/DH is largest at Annamalainagar. The ratio DZ/DH showed a minimum before midday hours at all the equatorial stations TRD, KOD and ANN while at ABG a small maximum was seen in the afternoon hours.
- It is important to note that DZ/DH at TRD was more than 1.0 at any hour of day. Further the value was larger during nighttime hours than during the day. The whole day mean value of DZ/DH was 1.23 for TRD, 0.42 for KOD, 0.45 for ANN and 0.26 for ABG.





- The ratio *Z/H, however, shows a distinct maximum during* local winter and a minimum during local summer months.
- Thus, seasonally the electromagnetic induction effects are not largest when
- the strength of the electrojet current is largest but are controlled by the season.
- To check any effect of the solar cycle on the induction phenomenon, yearly mean values of midday peak of *H, forenoon peak of Z and the ratio of these peaks (Z/H) at Trivandrum are shown*
- in Fig. 6(c). The values of *H and Z were maximum around* 1981 and 1991, suggesting a direct relation with solar activity. The ratio *Z/H does not indicate any solar cycle variation at all. The* average value of *Z/H was around 0.20 at Trivandrum*

Month to month variations of the daily range of *H and Z as* well as the ratio *Z/H averaged over the period 1978 to 1995. (c) The* yearly mean midday peak deviation of the *H field and the forenoon peak* values of the *Z field from the respective midnight base value for each of the* years 1978 to 1995. (Rastogi, 2004)



- Among the stations, higher magnitude of **dZ/dH were noticed at TRD. This as result of coastal effect which influence the induction effect at the staion. (Rabiu and Nagarajan, 2008)**

Mass plot of the day time hourly values of (a) dZ/dH (b) one hourly Harmonics

聞いていただきありがとうございます

Watashi ni kiite itadaki arigatōgozaimasu

Thanks for Listening

安全な旅

Anzen'na tabi

safe journey