On the electric current systems in the Earth's environment
some historical aspects
Part I : external part / ionosphere / quiet variation

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Abstract :
In this paper we present some historical aspects on ionospheric electric currents. Our attention is focused on the regular part of these currents at the origin of the daily Earth's magnetic field variation S_R.
The steps described in this paper correspond to advances in fundamental physic, as well as in technology, data interpretation or other factors. The paper covers the period from 1870 up to now.

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Introduction :
The study of ionospheric electric current systems is strongly related to that of the Earth magnetic field, that is why our first part will present the Chapman and Bartels 's work concerning the main historical steps of geomagnetism up to about 1850. In this first part we underline the geomagnetism advances important for our purpose. In a second part we recall some definitions concerning the variations of the magnetic field to help the reader in understanding the scope of this study. Then we present the main steps. It is not a review, it is just some flashes with some historical notes.

I. Historical steps on geomagnetism: relations with the ionospheric electric current

Chapman and Bartels's work (1940) summarized in their book the main steps of geomagnetism history (see table 1).

Long time before Jesus-Christ, Chinese were knowing the Earth's magnetic field existence, but it is only at the beginning of the middle age that the Earth's magnetic field measurements started in Europe.
During several centuries, sparse observations of the magnetic field declination and inclination were made over the world.

In 1600, Gilbert introduced the concept of terrestrial magnet, allowing the global approach of the Earth's magnetic field. After Gilbert's work, all the sparse data were related together through a common picture (see figure 1)

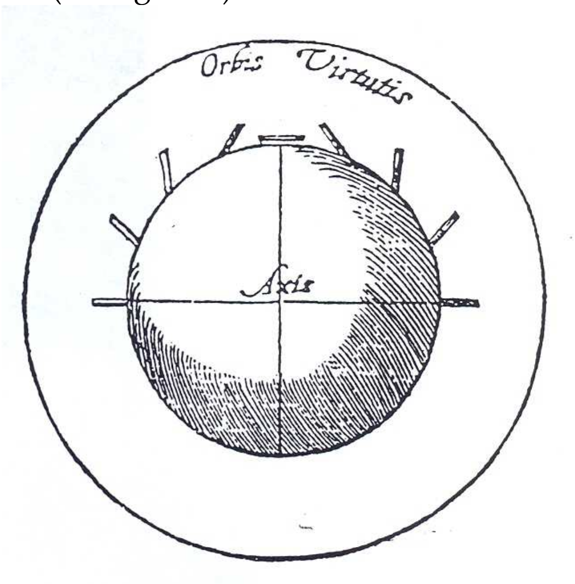


Figure 1 : Variety in the declinations of iron spikes at various latitudes of a Terrella,
[from Gilbert 1600 (book of Chapman and Bartels, 1940).]

Commentaries concerning Gilbert (Chapman and Bartels 's book, page 921) :
"S.P. Thompson, in notes (p 54) to the 1900 English edition, wrote : " Gilbert's extraordinary detachment from all metaphysical and ultraphysical explanations of physical facts, and his continual appeal to the test of experimental evidence, enabled him to lift the science of the magnet

out of the slough of the dark ages, ...However it still gave credence to the nativities of judicial astrology, and the supposed influence of the planets on human destiny."
It is not surprising that Gilbert's work also contained errors more nearly affecting magnetism, such as the conclusion (Chapter 3, book 4) that the variation (i.e. D) in any one place is constant : "Unless there should be a great dissolution of a continent and a subsidence of the land such as there was of the region Atlantis of which Plato and the ancients tell, the variation will continue perpetually immutable".
Gilbert's book was received with great favour in his time, though some parts of it were considered heretical by many because they upheld the Copernican views, of which he was the first English adherent; Galileo's copy book was given to him by " a Peripatetic Philosopher, of great fame, as I believe to free his library from its contagion"; the Jesuit scientists, however, who followed Gilbert in their magnetic writings, were right in repudiating his idea that "The needle was counterpoised by a small piece of brass."

This magnet approach led to the establishment of the first magnetic field map in 1701, by Halley (see figure 2).

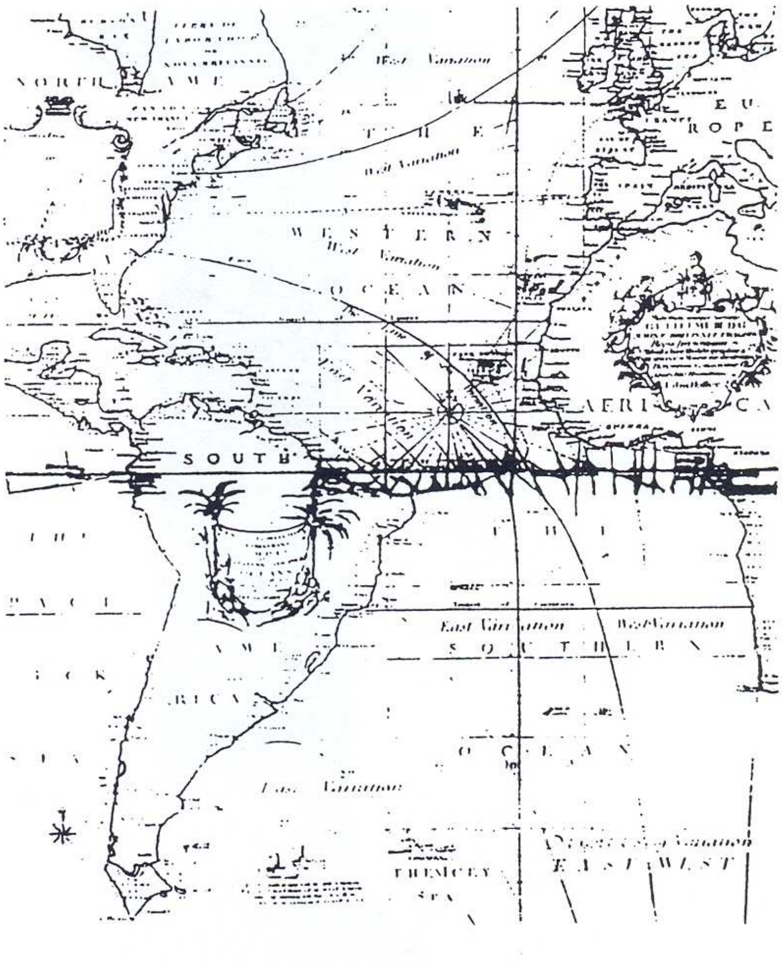


Figure 2 : First map of the Earth's magnetic field, Halley, 1701
[from the book of Chapman and Bartels, 1940]]

During the seventeenth century and the following centuries, various magnetic field variations were recorded : the secular variation by Henri Gellibrand in 1635, the regular and disturbed daily variations respectively by George Graham in 1722 and Celsius in 1741.

The observation of the daily regular variation of the Earth's magnetic field must be considered as the starting point of the study of regular ionospheric electric current.
From 1700 to 1750, relations were made between the magnetic field variations and the aurora (Celsius 1741) and between the aurora and the magnetic field (Wilcke).

It is only at the beginning of the nineteenth century that A. Von Humboldt named magnetic storms all the sporadic phenomena observed on the magnetic field which do not correspond to the daily variation. These variations are related to disturbed ionospheric or magnetospheric current systems out of the scope of this paper. A. Von Humbold can be considered as a pioneer for systematic and simultaneous measurement of the magnetic field.

During the same period Weber and Gauss contributed to the development of experimental geomagnetism studies by the creation of the Göttingen Union.

Commentaries from Chapman and Bartels concerning the participation of Weber and Gauss to geomagnetism studies (p 931) :
"*The Göttingen Magnetic Union : Gauss and Weber at the new Göttingen observatory, began, in March 1834, to participate in von Humboldt's scheme of simultaneous observations. Later they considered it necessary to make observations oftener than once an hour, and proposed 5-minutes intervals. A number of observatories associated themselves with this proposal in what became known as the Magnetische Verein (Göttingen Magnetic Union). Three to six periods of simultaneous observation, each extending over 24 hours, were agreed upon annually.*"

The systematic observations of the Earth's magnetic field variations simultaneously by different observatories is one of the fundamental experimental steps in the studies of the regular ionospheric current system.

During the second part of the nineteenth century, other relations between the magnetic field and the sunspot cycle (discovered by Schwabe in 1851) were established.

In 1850, nobody was thinking that electric currents flowing around the Earth could be responsible of the diurnal variation of the earth magnetic field. People were thinking that telluric currents were the cause of this diurnal variation and measurements of telluric currents were developed over the world during the nineteen century.

On the Earth 's Currents ...... By the Rev. Humphrey Llyod (1861 :
"*When the discovery by Oersted had made known the connexion which subsists between magnetism and current electricity, the idea occurred to many that the magnetism of the Earth, or at least, its diurnal fluctuation, was the result of electric currents traversing its crust. The idea gained much force from the fact, soon after discovered by Seebeck, that electric currents are generated when heat is applied to a circuit composed of different metals; and it was supposed that the phenomena were thus traceable to the thermal agency of the sun, operating in succession upon the conducting substances of which the earth's crust is composed.*

The most explicit statement, and chief support of this hypothesis, is contained in a memoir by Professor Christie, published in the Philosophical Transactions in 1827. "

If people were thinking that the regular variation of the Earth magnetic field was due to internal current, they were also relating the disturbed magnetic variations "magnetic storms" to atmospheric phenomena (external electric currents) as they observed a relation with aurora.

We must notice here that in 1733 J. Dortous de Mairan, gave the right explanation for aurora phenomena:

J-J de Mairan et l'Origine des Aurores, J-P. Legrand :
" L'aurore boréale est un phénomène lumineux ainsi nommé parce qu'il a coutume de paraître du côté nord, ou de la partie boréale du ciel, et que sa lumière, lorsqu'elle est proche de l'horizon, ressemble à celle du point jour, ou à l'aurore. Sa véritable cause est, selon ce que je pense, la lumière zodiacale. .....
Et Mairan de poursuivre en indiquant que cette matière qui compose l'atmosphère solaire vient rencontrer les parties supérieures de notre air et tombe dans l'atmosphère terrestre à plus ou moins grande profondeur. cette matière s'enflamme soit spontanément, soit "par collision avec les particules de l'air".

II. On the Earth's magnetic variations, some recalls useful to understand the scope of this paper

The Earth magnetic field can be expressed as follows:

$$\mathbf{B = Bp + Ba + Be + Bi}$$

Bp : main field (core- internal source)
Ba : magnetization field (lithosphere and crust - internal source)
Be : external field (ionosphere, magnetosphere - external source)
Bi : telluric field (Earth, coupling between external / internal)

The main field amplitude varies from 30 000 nT to 60 0000 nT between the equator and the pole, on the contrary the Ba field amplitude is quasi constant and its magnitude is 20 nT.
The magnitudes of the Be and Bt components due to external sources fluctuate between 10 to 1000 nT depending on latitude and time. They are not independent, the external regular ionospheric currents are at the origin of the regular telluric currents, they are proportional.
The main field Bp varies at the secular scale time and does not contribute to the daily variation of the Earth magnetic field.
The Be and Bi components have scale time variations from a fraction of second to the solar cycle (11 years). They include the regular daily variation of the Earth's magnetic field generated by ionospheric currents circulation.

The daily variation of the Earth magnetic field is composed of a regular part S (solar) and a disturbed part D (disturbed) .

$\Delta Be = De + Se$ and its associated $\Delta Bi = Di + Si$

The disturbed daily variation of the Earth magnetic field (out of the scope of this paper) can be expressed as follow:

$$De = D_p + D_R + D_{CF} + D_T \text{ (Akasofu and Chapman, 1961)}$$

All the disturbed component are associated to an electric current system circulation in the ionosphere, magnetopshere and along the magnetic field lines.

D_p : Disturbed ionospheric current

D_R : Ring current

D_{CF} : Chapman Ferraro currents (magnetopause)

D_T : Tail current

The geometry of all the external current systems is given on figure 3 from Heikkila, 1972.

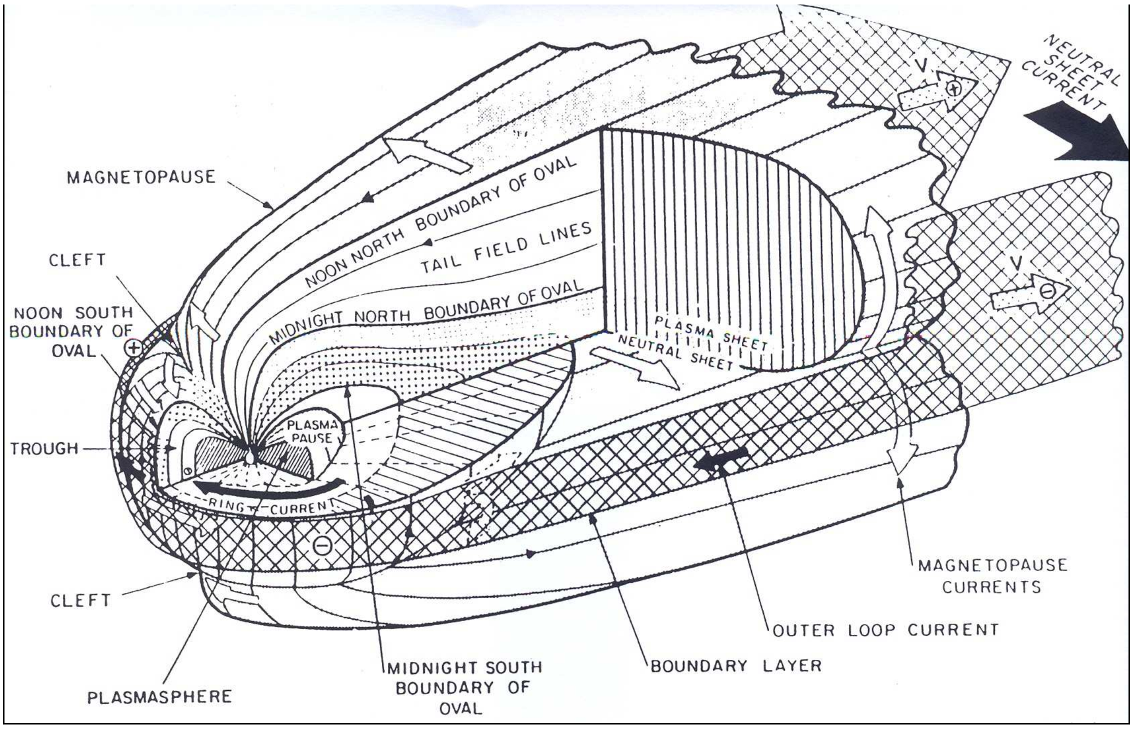


Figure 3: Geometry of the magnetospheric current systems
at the origin of the D field. [from Heikkila, 1972]

The regular part S is considered as mainly due to the daily regular ionospheric current circulation (scope of our paper). The geometry of this system is given on figure 4.

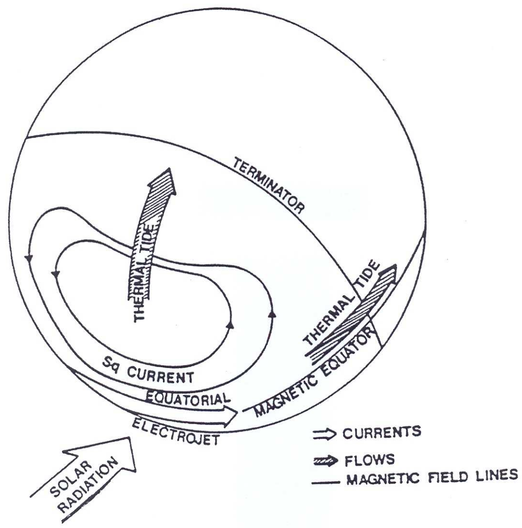


Figure 4 : Rough geometry of the ionopsheric current system
at the origin of the regular variation of the Earth's magnetic field.

The various external current systems are generated by different interaction between the sun and the Earth's environment.
The S_R current system is related to the atmospheric dynamo, which generates electric current by the conversion of atmospheric motion in electricity. The D current systems are in general more or less directly related to the solar wind dynamo. In this last case, it is the motion of the solar wind in the interplanetary medium the primary generator of electric currents.

III. Historical steps on ionospheric electric currents

After all these considerations on the Earth's magnetic field, we can highlight some main steps of electric ionospheric currents history.

The selected steps are summarized in table 2, they concern :
- **Fundamental sciences : electromagnetism, mathematics, etc ..**
- **Technologies : radar, rocket flights**
- **Interpretation of observations : concept, theories**
- **Conceptual tools : parameterization**
- **International organization and choice of classifications**
- **Computer organization : data base**

Three men played a dominant role in the ionospheric current history :
- J. Maxwell
- B. Stewart
- A. Schuster

MAXWELL J. was thinking that the development of experimental science as geomagnetism was essential for the progress of science

At the end of the nineteenth century, fundamentalist researchers as Maxwell were interested in the development of geomagnetism as a field of experimentation for the electromagnetism theory. A part of his introductory lecture on experimental physics at Cambridge in 1870, is devoted to geomagnetism :

" *But the history of the science of terrestrial magnetism affords us sufficient example of what may be done by Experiments in Concert, such as we hope some day to perform in our laboratory.*
That celebrated traveller, Humboldt, was profoundly impressed with the scientific value of a combined effort to be made by the observers of all nations to obtain accurate measurements of the magnetism earth....
We must reserve for its proper place in our course any detailed description of the disturbances to which the magnetism of our planet is found to be subject. Some of this disturbances are periodic, following the regular courses of the sun and moon. Others are sudden and called magnetic storms, but, like the storms of the atmosphere, they have their known seasons of frequency. The last and the most mysterious of these magnetic changes is that secular variation by which the whole character of the earth, as a great magnet, is being slowly modified, while the magnetic poles creep on, from century to century along their winding track.
We have thus learned that the interior of the earth is subject to the influences of the heavenly bodies, but that besides this there is a constantly progressive change going on, the cause of which is entirely unknown."

It is interesting to notice that in these commentaries, Maxwell related the magnetic variations to the sun, the moon, the atmosphere and the interior of the earth.

And Maxwell also commented on Human nature, one of the most important parameter in History of science (not taken into account in this paper) :
" *The men whose names are found in the history of science are not mere hypothetical constituents of a crowd, to be reasoned upon only in masses. We recognise them as men like ourselves, and their actions and thoughts being more free from the influence of passion, and recorded more accurately than those of other men, are all the better materials for the study of the calmer parts of human nature.*
But the history of science is not restricted to the enumeration of successful investigations. it has to tell unsuccessful inquiries and to explain why some of the ablest men have failed to find the key of the knowledge, and how the reputation of others has only given a firmer footing to the errors into which they fell.
The history of the development, whether normal or abnormal, of ideas is of all subjects that in which we, as thinking men, take the deepest interest. But when the action of the mind passes out of the intellectual stage, in which thruth and error are the alternatives, into the more violently emotional states of anger and passion malice and envy , fury and madness; the student of science though he is obliged to recognize the powerful influence which these wild forces have exercised on mankind, is perhaps in some measure disqualified from pursuing the study of this part of human nature."

Maxwell 'work on the relations between the electromagnetism laws (1873) was fundamental for the studies of ionospheric currents, and few years later, the hypothesis of electric current flowing outside the Earth was proposed by B. Stewart (1882-1886), to explain the daily regular variation of the magnetic field.

STEWART B. introduced the concept of external electric current to explain the daily regular variation of the Earth's magnetic field

At this time three other hypothesis were proposed to explain the regular magnetic field variation:

- Direct action of the Sun upon the earth
- Heating effect of the Sun on the chief mass of the Earth's atmosphere(Faraday's hypothesis)
- Earth currents

B. Stewart: On the Cause of the Solar-Diurnal Variations of Terrestrial Magnetism, communication by the Philosophical Society, April 10, 1886.
" *Now, if it be unlikely that these magnetic variations are caused either by the direct magnetic action of the Sun, or by earth-currents, or by the heating effect of the Sun on the chief mass of the Earth's atmosphere, we seem to be driven by the method of exhaustion to look for their cause in the upper atmospheric regions. We shall, however, have to show that there is no improbability in locating their cause in these elevated regions, otherwise our method of exhaustion will have done us no service. In the first place, I need hardly say that if the cause we are in search of be in these upper regions, it must either be in the shape of a set of electrical currents, or in some other shape which we are quite unacquainted; but the nature of this discussion precludes us from entertaining the latter supposition; and we are therefore driven to regard electrical currents as being the only conceivable cause, if the cause is to be located in the upper atmospheric regions.*
I shall now attempt to reply to two imaginary objections that may be raised as to the possibility of such currents. In the first place, it may be said that while undoubtedly rarefied air is a conductor of electricity, yet it is not a good conductor; and where can we look for sufficient potential to drive currents through these upper atmospheric regions? To this I would reply that as a matter of fact we know that there are visible electric currents in the upper atmospheric regions of the Earth. .... I allude to the Aurora which is unquestionably an electric current, and must therefore influence the magnetic needle. "

On Balfour Stewart who was an universal mind by Dr Shuster: Memoirs and Proceedings of the Manchester and Philosophical Society (1888), Fourth Series, First Volume, p 253-272.

"Balfour Stewart's name was first prominently brought before the public by his researches on radiant Heat ."
" *Balfour Stewart was the author of several text -books. His «Primer of Physics", as well as his "Elements of Physics" ....."Lessons in Elementary Practical Physics", written jointly with Mr W.W. Haldana Gee... An admirable treatise on the "Conservation of Energy" .. Students of Terrestrial Magnetism will for a long time to come to the clear and at the time full account he has given of the present state of the subject in the last edition of the "Encyclopaedia Britannica".*
His book "The Unseen Universe, or Physical speculations on a Future State", by Stewart and Tait, was published anonymously at first. It went rapidly through several editions, and in the fourth the author's names were given.

The following abstract from the preface to the first shows the aim of the book
«Forgetful of the splendid example shown by intellectual giants like Newton and Faraday, and aghast at the materialistic statements now-a-days freely made (often professedly in the name of science), the orthodox in religion are in somewhat evil case.

" As a natural consequence of their too hastily reached conclusion that modern science is incompatible with Christian doctrine, not a few of them have raised an outcry again science itself. this result is doubly to be deplored, for there cannot be a doubt that it is calculated to do mischief not merely to science but to religion.

" Our object, in the present work is to endeavour to show that the presumed incompatibility of Science and Religion does not exist. This, indeed, ought to be self-evident to all who believe that the Creator of the universe is Himself the Author of Revelation. But it is strangely impressive to note how very little often suffices to alarm even the firmest human faith."

Balfour Stewart was an active member - at one time the President - of the Psychical Society; believing that every subject must gain by an impartial and philosophical inquiry, and that no subject is beneath the attention of scientific men.
He received the Rumford medal of the Royal Society in 1868. At the time of his death he was President of the Physical Society of London, and of the Manchester Literary and Philosophical Society."

SCHUSTER A. (1851-1934) was the first to separate the internal and external sources of the Earth's magnetic field and to establish the first map of equivalent current system.

A. Shuster: the diurnal Variation of terrestrial Magnetism, received march 20- read 28, 1889 :
" *In the year 1839 Gauss published his celebrated Memoir on Terrestrial Magnetism in which the potential on the Earth's surface was calculated to 26 terms of a series of surface harmonics. It was proved in this Memoir that, if the horizontal components of magnetic forces were known all over the Earth, the surface potential could be derived without the help of the vertical forces, and it is well known now how these latter can be used to separate the terms of the potential which depend on internal from those which depend on external sources....*
The Use of harmonic analysis to separate internal from external causes has never been put to a practical test, but it seems to me to be especially well adapted to enquiries on the causes of the periodic oscillations of the magnetic needle...
The agreement seemed to me to be sufficiently good to justify the conclusion that the greater part of the variation is due to causes outside the Earth's surface.....
The results of the calculation point not only to an external source, but to an additional internal source, standing in fixed relationship to the external cause"

A. Schuster with his technical work on the daily variation proved that external sources are at the origin of this regular variation (Be) and found the associated telluric part induced by external source (Bi).
A. Schuster used one year of data from four stations (Lisbon, Greenwich, Bombay and St Petersburg) and he said:

" Four stations are sufficient to find to the necessary accuracy the potential on the surface of the Earth, but it would be of advantage if in future similar investigations a greater number of stations could be utilised."

Then A. Schuster established the first map of equivalent electric current system, he supposed that the current were flowing in a concentric layer having a thickness of about 30 miles and surrounding the Earth at 1000 km of altitude:

" *If we imagine the variable part of the magnetic force (daily variation) to be produced by a system of surface currents in a conducting sphere concentric with the Earth, and surrounding it, we may, if the potential is known, calculate the distribution of the lines flow....*
We conclude that we may imagine the daily variation of the Earth's magnetic force to be produced by a system of electric currents in a sphere surrounding the Earth, in which lines of flow are roughly represented in fig. 12 (figure 5, here), the direction being such as that at longitude 60° East the flow is away from the equator."

Comments on A. Schuster by S. Chapman in Terrestrial magnetism and Atmospheric Electricity (1934), Vol 39. :
" *His own work, on electrical conductivity of gases, had already helped to remove a difficulty then left, as to the possibility of air being able to convey necessary currents. In 1907 he returned to the subject, and elaborated this "dynamo" theory mathematically. He assumed a periodic system of air-currents, associated with the daily barometric variation and calculated their effect, assuming a distribution of electric conductivity in the upper air, depending on the Sun's zenith-distance. He attributed the conductivity to ionization by ultra-violet radiation, and was able to make an estimate of the total conductivity of the current-bearing layer.*"

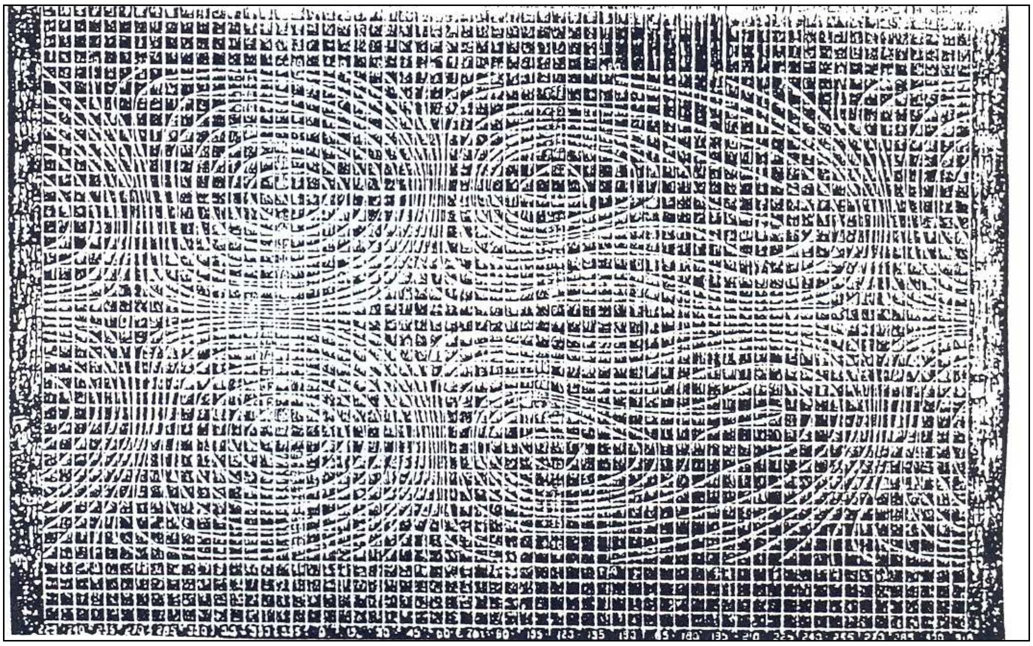


Figure 5: Fist map of equivalent current system
[by A. Schuster in 1889.]

Remember that at the end of the nineteenth century, the ionospheric layer was not yet discovered. With the discovery of the ionosphere in 1901 by Marconi, and the concept of ionosphere by Kenelly and Heaviside, a new path for the study of ionospheric electric currents was opened by the access to in situ measurement. And then two experimental paths were followed during the next century: 1) access to "equivalent ionospheric current" by using magnetic data from many observatories and 2) development of techniques to measure in situ parameters useful for the computation of electric currents. Since 1940, advances in different directions: dynamo theory, conductivity in a partially ionized gas and atmospheric tides allowed a global physical approach of the daily regular variation of the Earth's magnetic field.

In order to facilitate the comprehension we will analyse the development during the twentieth century following the three topics:

- magnetic data analysis
- in situ measurement of ionospheric and atmospheric parameters
- theories

MAGNETIC DATA ANALYSIS :

In 1905, The classification of the 5 international quiet days by the international Commission at the Innsbruck Conference, was essential to develop systematic studies on the regular variation.

S. Chapman using the classification given at Innsbruck, established electric current maps using the magnetic field variations averaged over the five quietest days of one month. This current system was named the Sq current system (see figure 6). Many works analysing the solar cycle, seasonal and diurnal variation of the Sq current was made later.

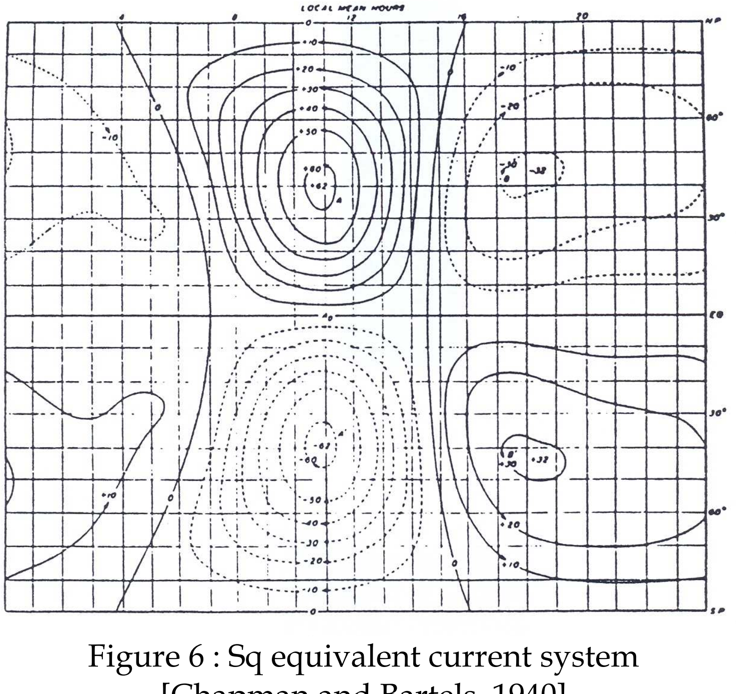


Figure 6 : Sq equivalent current system
[Chapman and Bartels, 1940]

Equivalent current system

Figure 7 shows the ideal Sq equivalent current system. The electric current system closed separately on each hemisphere. World magnetic variations observed at ground level have been expressed by the equivalent current system on the assumption that the geomagnetic variation fields are only produced by the ionospheric current flowing in a thin infinite two-dimensional layer . The relation between the variation of the Earth's magnetic field (B in nT) and the electric current densities integrated over the dynamo region (J in Amperes per kilometre) is : $\Delta B = (2\pi/10f.J)/$, f is a factor taking into account the telluric currents.

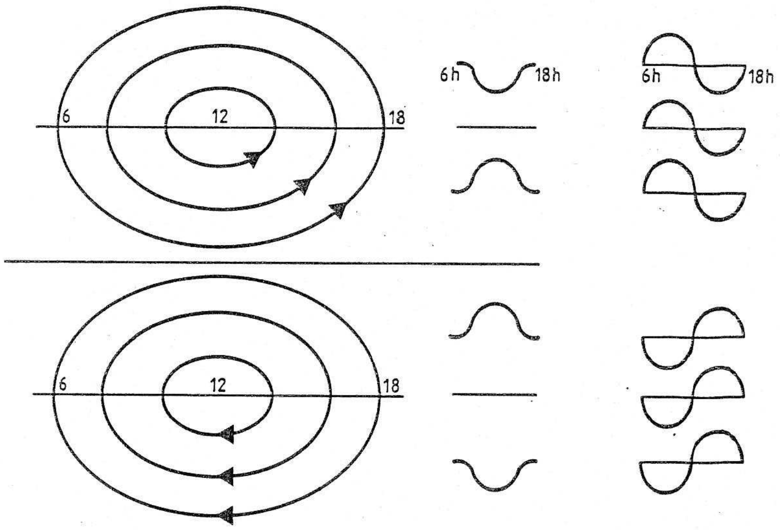


Figure 7: Ideal Sq equivalent current system

Later, in 1962, Price and Wilkins performed the computation of equivalent current systems (figure 8) which revealed the asymmetries of current circulation between the two hemispheres even during quiet time (Van Sabben, 1964, 1966; Fukushima, 1951). This asymmetry implies the circulation of electric current between the two hemispheres and therefore infers the tri dimensional nature of the regular current system.

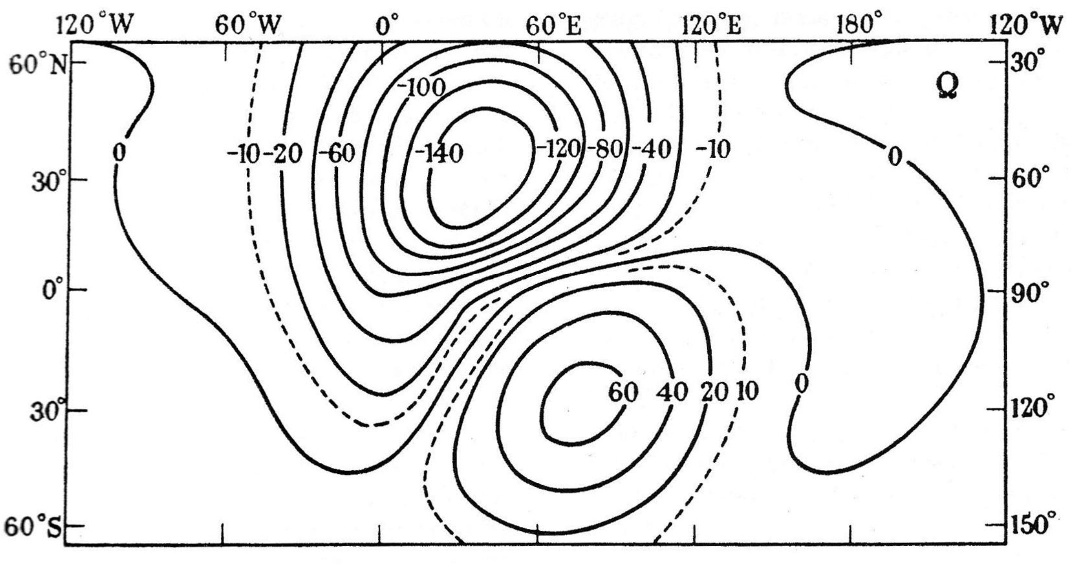


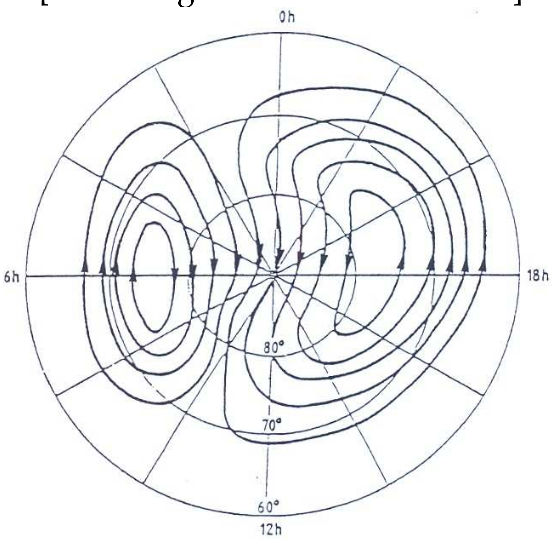
Figure 8 : Analysis of the geomagnetic fields showing the asymmetry between the two hemispheres [by Price and Wilkins (1962)]

Price and Wilkins: New methods for the analysis of geomagnetic fields and their applications to the Sq field, 1963:

"*Spherical harmonics express an important part of the field in analytic form suitable for theoretical work, such as the separation of the field into parts of external and internal origin. In the methods we have developed, the advantage of an analytic expression is scarified and the separation of the* *field is much more laborious, since it involves the numerical evaluation of a large number of surface integrals. This, however, is less important than formerly, now that the burden of heavy numerical work can be greatly eased by modern computers.*"

The magnetic field observations were performed all over the world:
In 1931, the observation of the magnetic field at Huancayo (near the equator) led to the concept of equatorial electrojet (Chapman in 1951). This current flowing along the equator produces a regular variation with a magnitude one and a half to twice greater than at middle latitudes.
In 1962, Nagata and Kokubun, proposed the Sq^p equivalent current system for the magnetic variations observed at high latitudes (figure 9). we must recall here that these variations are related to the corpuscular solar source and do not concern this paper.
In 1965, P. N. Mayaud introduced the S_R current system, the difference with the Sq one is that this current is not averaged over the five quietest days, it represents the daily regular variation of one day. The analysis of the day-to-day variability of the S_R, in relation with the day-to-day variability of ionospheric parameters allowed to detect the individual magnetic signature of ionospheric phenomena.

Figure 9 : S_q^p current system
[from Nagata and Kokubun 1962]



Nowadays, the ground magnetic variations are still used to derive equivalent current system and remain very useful as they give access to the planetary scale of electric current.

Commentaries from Y. Kamide in Electrodynamic processes in the Earth's ionosphere and magnetosphere , 1988 (page 611 et 612):

" *It should be noted that the equivalent ionospheric current faces some severe limitations in order to estimate the distribution of the real (not equivalent) current and electric field as summarized by Stern (1977), there are at least three reasons for these limitations. First, even if observational coverage is perfect and all currents are confined to the ionosphere, the equivalent currents provide only an approximation of the true current system. Second, the influence of the field-aligned current portion of the electric current circuit on geomagnetic variations is far from negligible. Third the electric field is simply related to the current density, since the ionospheric conductivity is a tensor* *and depends on altitude, solar zenith angle, and any particle precipitation that might be taking place. However, if the ionospheric conductivities can be inferred with reasonable accuracy (this may not be difficult for quiet periods), it is possible to derive the electric potential over the two-dimensional surface."*

IN SITU MEASUREMENTS:

From 1925 to 1930, many progresses in the field of wave propagation in the ionosphere (Appleton and Hartree) were made and in 1925 the first measurements with the ionosonde technique performed by Breit, allowed to know the height profile of ionosphere and the electronic density created by the solar ionization.

From 1958 to 1965 new techniques such as rocket flights (1960-1965) giving access to atmospheric tides (Siebert, 1954, 1956) and incoherent scatter sounder (1958-1966) (W.E. Gordon, 1958; J-P. Dougherty and D.T. Farley, 1960) giving access to electric conductivity, electric field and current as well as atmospheric tides (Vasseur, 1969; Woodman, 1970; Brekke et al., 1974) were applied.

From 1960 up to now these in situ measurements were and are still used for developing empirical models of the atmospheric parameters (Jacchia, 1964, 1971, MSIS 1986) and ionospheric electric current (Salah and Evans, 1977; Mazaudier and Blanc, 1982). Figure 10 (Mazaudier and Blanc, 1982), shows the diurnal variations of ionospheric electric currents observed in the European sector (Saint-Santin: 44°6N, 2.2°E) and in the American sector (Millstone Hill : 42.6°N, 71.5°W). It is clear that the observations made at European longitude reveal the north-south asymmetry of the regular current system and therefore its three-dimensional nature.

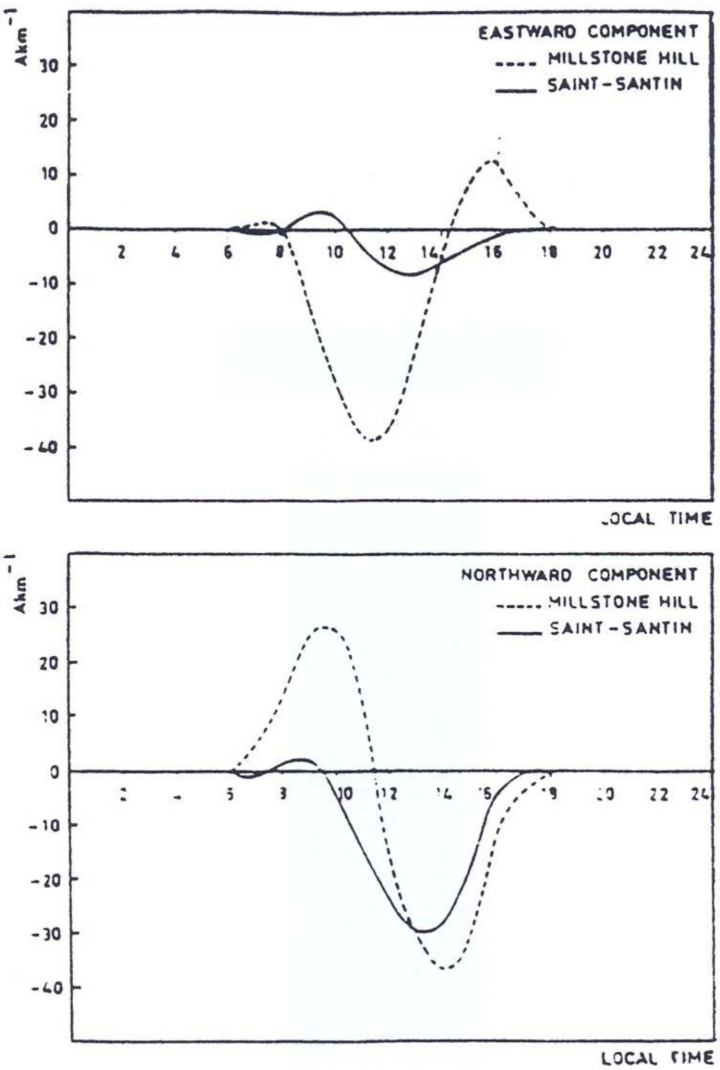


Figure 10 : Ionospheric electric current measurement from incoherent scatter sounder (Salah and Evans, 1977; Mazaudier and Blanc, 1982). The comparison of the current models of Millston Hill (dashed line) and Saint-Santin (solid line) shows rather large differences. The differences in the east-west current can be simply explained by the different magnetic latitudes of the two stations, since Saint-Santin is close to the Sq focus latitude, whereas Millstone Hill is north of it. But the difference in north-south currents requires the addition that a longitude variation of the current system be present

THEORIES:

From 1940 to 1960, advances in dynamo theory (Chapman) and partially ionized gas theory (Cowling, 1942, 1945) were essential to progress in the knowledge on ionospheric current.

The dynamo theory including the ionospheric Ohm's law : $J= \sigma (E + Vn \times B)$ expressed the electric current in terms of its constitutive parameters (σ : conductivity, Vn : neutral wind, E : electric field).This theory was first developed on the basis of the experimental studies based on magnetic and ionosonde data. It aimed at understanding the system of Sq ionospheric currents in terms of a global distribution of neutral winds (Kato, 1956; Maeda, 1955). Until 1960, the development of dynamo theories lacked the support of experimental access to the altitude and local time variation of the E region neutral winds and electric fields.

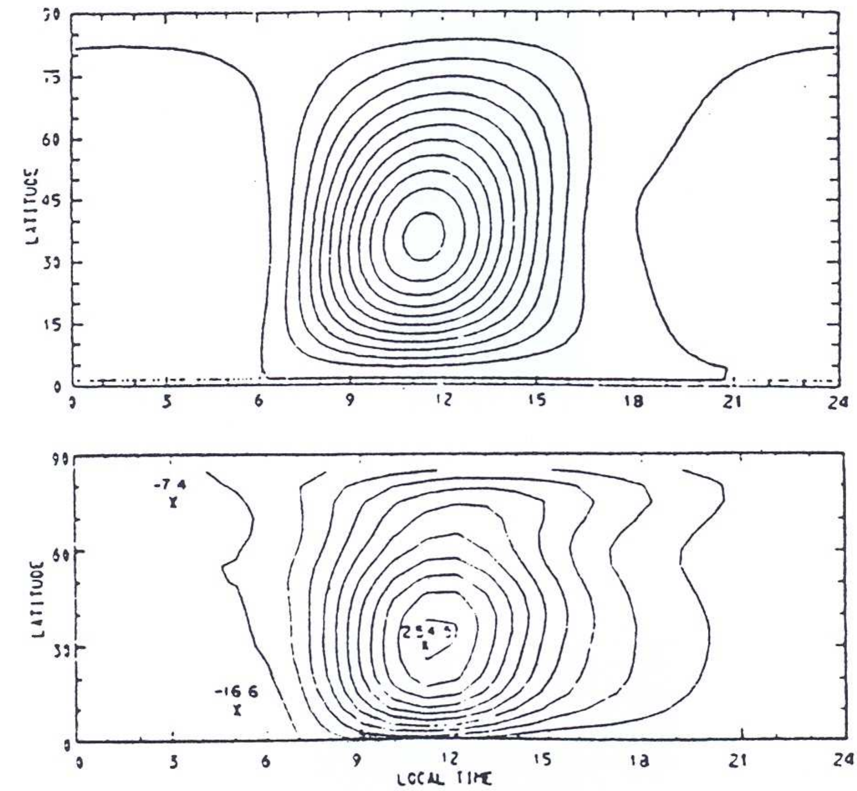


Figure 11: Numerical simulations of Electric currrent system [Richmond et al., 1976].Top: Current function in the northern hemisphere produced by the modified $S_{1,-2}$ tidal mode and $S_{2,4}$ mode, with amplitudes and phases as indicated by wind observations. Contours spacing is 10 kA, and the current flows clockwise during the day. Bottom: Sq current function from IGY geomagnetic data.Contour spacing is 25kA. The difference between the computed and observed current intensities can be largely explain by the difference in the assumed solar cycle conditions (moderate-low) from IGY conditions

On the basis of wind measurements, the theory of atmospheric tides was developed by Chapman and Lindzen in 1970 and the two dimensional computation of electric current was performed (Stening, 1969; Tarpley, 1970; Richmond et al., 1976). Figure 11 from Richmond et al., shows the current system computed with the dynamo theory using in situ measurement (top panel) and the current system deduced from the magnetic data (Matsushita 1968- bottom panel).

At the present time, data are set up together in data centres and tri dimensional models of the ionospheric dynamo are performed in order to reproduce as well as possible the observations.

CONCLUSION

Through some historical aspects the close relation between the regular Earth magnetic field variation and the system of ionospheric electric currents at the origin of these variations has been highlighted.

1. On geomagnetism we can retain the following:

- sparse data can be related together through a common picture once a concept is formulated (concept of magnet by Gilbert in 1600)
- well organized data (simultaneous measurements on a global scale) give rise to relations between constitutive parts of the phenomena under study.

2. An advance in fundamental physics was essential :

Maxwell's treatise set up the theoretical basis for the study of ionospheric electric current system, and we must notice that Maxwell in his introductive lecture at the Cambridge University, in 1870, had a clear idea on the development of experimental science as geomagnetism and the importance of experimental data.

3. Two men played a dominant role:

B. Stewart and A. Schuster (1882- 1910) were the pioneers in the ionospheric electric current studies in introducing respectively the physical process (atmospheric dynamo) and the dynamo theory and mathematical tools.

4. A group of researchers using various techniques and developing models worked and still work on this subject:

- From 1882 until now, studies on the global electric current systems were mainly based on the study of two dimensional equivalent current system derived from magnetic variations.

- After 1900, the discovery of the ionosphere and the development of the technology played a dominant role giving access to in situ measurements of ionospheric parameters. But it is only with the technique of incoherent scatter sounder (years 1970-1980) that scientists were able to derive ionospheric electric current from incoherent sounder data. However these measurements of electric ionosphere current were punctual.

- Since 1940, the development of the dynamo theory and numerical simulations using both magnetic data and in situ measurements allows progress in the comprehension of the global three dimensional ionospheric current system.

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Table I : Summary of important events in history of geomagnetism up to about 1850 from CHAPMAN and BARTELS, 1940

A.D. 1030-93	The Chinese encyclopaedist Shon-Kua described the magnet pointing south
About 1187	Alexander Neckman of St. Albans described the magnetic compass
About 1450	Sun dials in Nuremberg showed marks for magnetic declination
About 1492	German roads maps containing the figure of a compass indicating the declination
1538-41	Joao de Castro, on a voyage to the East indies, made forty-three determinations of magnetic declination
1544	Letter by Georg Hartmann of Nuremberg, referring to the magnetic inclination
1576	Robert Norman *The Newe Attractive*
1600	William Gilbert, *De magnete*
1635	Henri Gellibrand discovered the secular variation of declination
1672	Daniel Tilas died (inventor of the Swedish mining compass for magnetic prospecting)
1698-1700	Halley's voyages in the Atlantic Ocean on the *Paramour Pink*
1701	Halley's sea chart of the whole world
1721	William Whiston's charts of inclination
1722	**George Graham discovered non-secular time-variations**
1741, April 5	Simultaneous magnetic observations by Celsisus at Upsala and Graham at London; discovery of the relation between magnetic disturbances and aurora
1759	**Solar daily** variation found to be greater in summer than in winter (by Canton)
1770	Wilcke observed that auroral rays are parallel to the magnetic inclination

1782 Cassini found that the **daily variation** of the declination is independant of the daily variation of air-temperature

1799-1804 A. von Humboldt's expedition to America

1819 Hansteen's *Untersuchungen über den Magnetismus der Erde*

1820-35 Arago's observations of the magnetic declination at Paris

1826 Poggendorff introduced readings by means of mirror and scale

1837 The Earth inductor invented by Weber

1838 Gauss *Allgemeine Theorie des Erdmagnetismus*

1839 Llyod introduced the magnetic balance for recording the variations of the vertical intensity

1836-41 The Göttingen Magnetic Union

1839 Establishement of the British Colonial Observatories (Sabine)

1846 Charles Brooke constructed photographic apparatus recording magnetic variations

1850 Kreil found the lunar daily variation of declination at Prague

1851 Schwabe discovered the sunspot cycle

1852 Sabine found the effect of the sunspot cycle in the disturbances of declination at Toronto, 1841-48.

Table 2 : Summary of important events in the history of regular ionospheric electric current (S_R magnetic field) up to about 1993

1722	**George Graham discovered non-secular time-variations**
1873	Treatise on electricity, Maxwell *lecture of 1870 at the Cambridge University*
1882-1886	Concept of Atmospheric dynamo *lecture of B. Stewart*
1886-1907	Maps of external current systems (A. Schuster) Establishment of the dynamo theory mathematically *Lecture, figure*
1901	Radio beacon (Marconi) Ionosphere postulated by Kenelly and Heaviside
1905	Classification of the 5 international quiet days International Commission at the Innsbruck Conference
1919	Sq equivalent current system (S. Chapman)
1925-29	Wave propagation in the ionosphere (E.V. Appleton, Hartree)
1925-26	First measurements with ionosonde (G. Breit and M. Atuve, E.V. Appleton and M.A.F. Barnett)
1931	First observations of H component of the magnetic field at Huancayo -> equatorial electrojet (1951-S. Chapman)
1940	Application of theory dynamo to ionosphere (S. Chapman) (Maeda, Y. Kato)
1945	Conductivity in partially ionized gas (T.G. Cowling)
1950-65	Rocket flights, in situ measurement of atmospheric tides M. Siebert
1958-60	Theory of incoherent scattering of radio waves by a plasma W.E. Gordon, J.P. Dougherty, D.T. Farley
1960 -	Starting point for the development of atmospheric models Jacchia (1960) ----------> MSIS (1986)
1962	Asymmetries of the two hemispheres => J_{II}

	A.T. Price and G.A. Wilkins, D. Van Sabben, N. Fukushima
1962	equivalent current system S_q^P , Nagata and Kokubun
1965	concept of the S_R and its day-to-day variability
1970	Theory of atmospheric tides (S. Chapman , R.S. Lindzen)
1969-1976	Computation of ionospheric electric currents from available wind data, R.J. Stening, J.D. Tarpley, A. Richmond
1967-1970	Equatorial counter electrojet (Gouin and Mayaud)
1963-	Observations with incoherent scatter sounder network 1969 : neutral winds (G. Vasseur) 1970 : electric fields (R. Woodman) 1974 : electric currents (A. Brekke et al.)
1977-1982	Semi empirical models of quiet ionospheric electric current Salah and Evans 1977, Mazaudier and Blanc, 1982
1980-	Tri dimensional global simulations of ionospheric electric currents