Chapter 12

Equatorial Ionosphere

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12 Equatorial Ionosphere

The Earth's magnetic field exerts a considerable influence over the ionosphere, separating the ionosphere into three broad regions.

- Low-latitude equatorial,
- Mid-latitude, and
- High-latitude polar region

Of the three, the mid-latitude region is the most studied and well understood.

The phenomena that occur at mid-latitudes also occur at both the low and high latitudes, including ionization by solar Extreme Ultra-Violate (EUV) radiation, diurnal and seasonal variation, as well as the changes created by the roughly 11 year solar cycle. In addition, the low and high latitudes each have phenomena that are unique to their particular regions. Consequently, the high-latitude polar ionosphere bears little resemblance to the low-latitude equatorial region, and both are considerably different from the mid-latitude ionosphere.

The previous chapter is primarily concerned with the mid-latitude ionosphere. This chapter focuses on the equatorial latitudes.

Earth's equatorial region is the zone between the Tropic of Cancer and the Tropic of Capricorn, 23.5 degrees either side of the equator (Figure 1).

Earth's magnetic field throughout the equatorial region is predominately horizontal (parallel to the Earth's surface) as illustrated in Figure 2. Energetic electrically charged particles from the magnetosphere and solar wind can not cross these magnetic field lines. Instead, the particles spiral along the field lines parallel to Earth's surface above the equator and plunge vertically into Earth's atmosphere in the polar regions as shown in Figure 2. The horizontal field above the equator shields Earth's low latitude regions from these energetic particles. The equatorial ionosphere is unique in that it is thicker than elsewhere. Also, in the equatorial region the Sun is nearly over head every day throughout the year resulting in extensive solar photo-ionization. Consequently, electron densities are higher in the tropics than at mid and polar latitudes with little seasonal variations between summer and winter. Based on these characteristics we would expect the low latitude region to be a quiet zone. To an extent our assumptions are true.

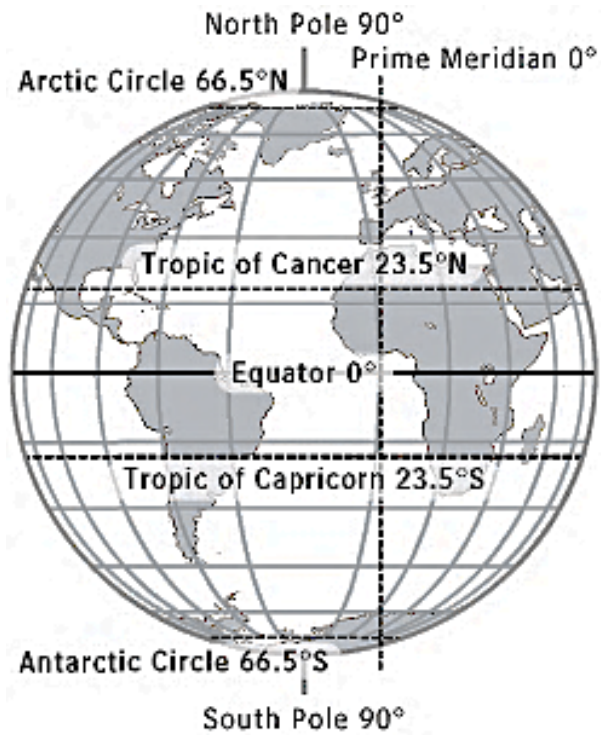

Figure 1 Regions of the Earth (source: google)

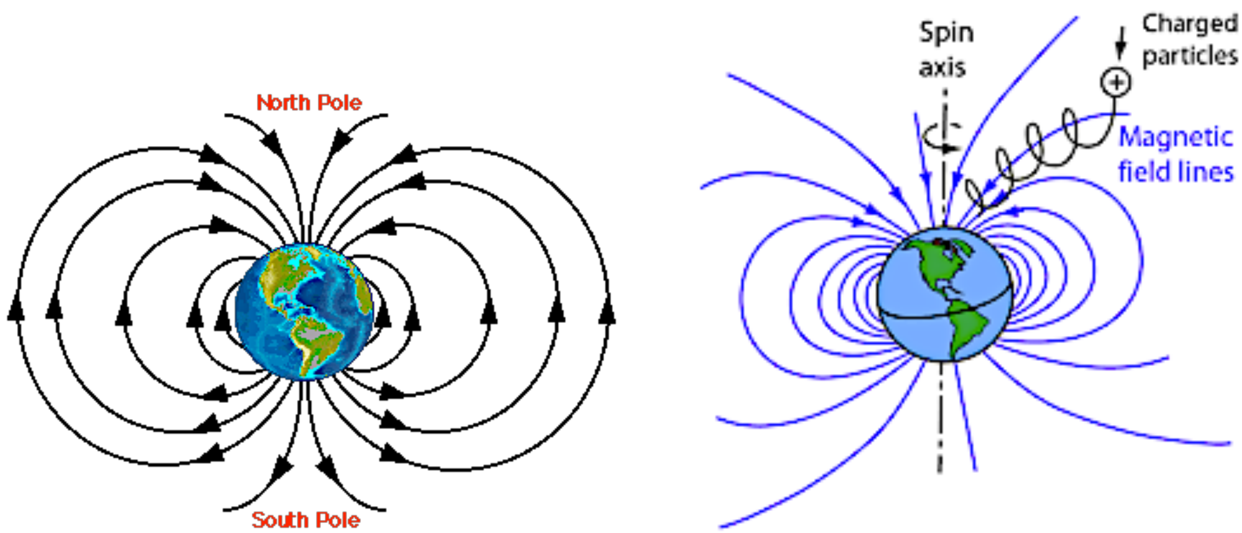

Figure 2 Earth's Magnetic field (source: The Ocean Web and hyperphysics)

However, strong electromagnetic forces are present in the equatorial zone. These forces result from:

- The Earth's horizontal north-south magnetic field over the geomagnetic equator, and
- High concentrations of free electrons resulting from extensive photo-ionization.

12.1 Dip Equator

The dip equator (also known as the magnetic equator) differs from the geomagnetic and geographic equators as illustrated in Figure 3. Not only are the equators different, but the geographic, geomagnetic, and the magnetic north poles are also in different locations. The same is true for the south poles.

The geographic equator is horizontal in Figure 3. The Earth's spin axis is perpendicular to the geographic equator and passes through the geographic north and south poles.

To a first approximation, Earth's magnetic field is a dipolar field as illustrated in Figure 2. The axis of this dipole field is tilted 11.5^{o} with respect to Earth's spin axis as shown in Figure 3. The geomagnetic equator is perpendicular to the dipole axis. However, Earth's actual magnetic field does not coincide with Earth's geomagnetic dipole field.

Earth's actual, or dip, magnetic equator is the dashed wavy line in Figure 3. It is defined as the line along which the angle of inclination I (or dip angle) of Earth's magnetic field is zero. That is, Earth's magnetic field is horizontal (parallel to Earth's surface) only along the dip equator. At all other locations a compass needle free to move in all directions will point downward, as illustrated in Figure 4, instead of being horizontal. The magnetic field lines are nearly vertical in the polar regions with dip angles approaching 90^{o} (Figures 2 and 4). Consequently, the same compass needle at the dip poles will be vertical (standing on end). Actual compass needles are constrained so that they can only rotate horizontally.

The dip equator does not coincide with the geomagnetic equator because secondary sources of Earth's magnetic field (ionospheric and magnetospheric electrical currents plus small amounts of crustal magnetism) distort the dipolar shape of Earth's primary (or main) field. Earth's main magnetic field is of course generated deep within the Earth in its liquid outer core (Figures 2 and 5). The secondary fields are very small in comparison to the main field, but never the less cause diurnal and seasonal variations in the strength of the main field.

The positions of the geomagnetic equator and poles assume that the geomagnetic field is perfectly dipolar. The dip equator and poles reflect the reality that, at Earth's surface, the geomagnetic field is not perfectly dipolar. It is distorted. It is interesting to note, however, that the field does become increasingly dipolar in shape as one gets further from Earth's surface.

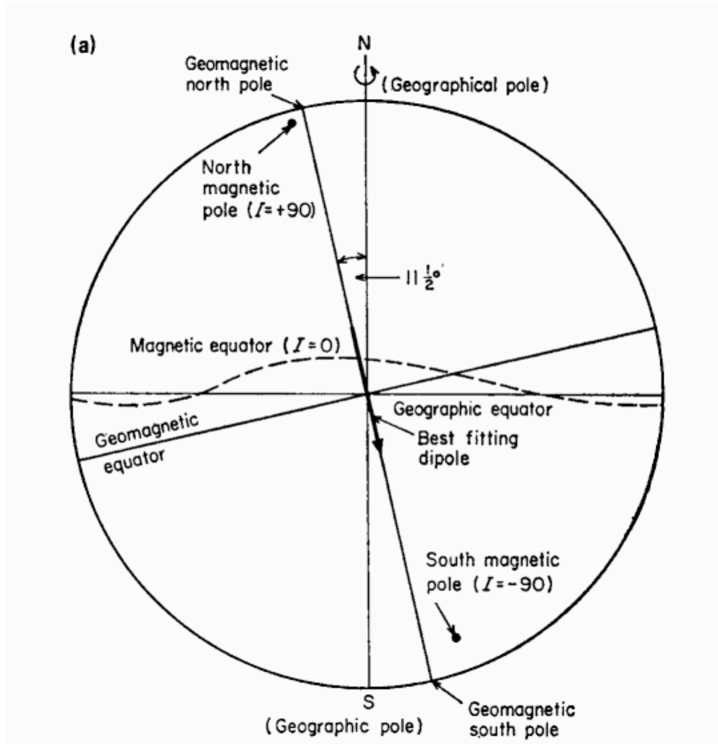

Figure 3 Geographic, Geomagnetic, and Dip Equators (source: www.ux1.eiu.edu)

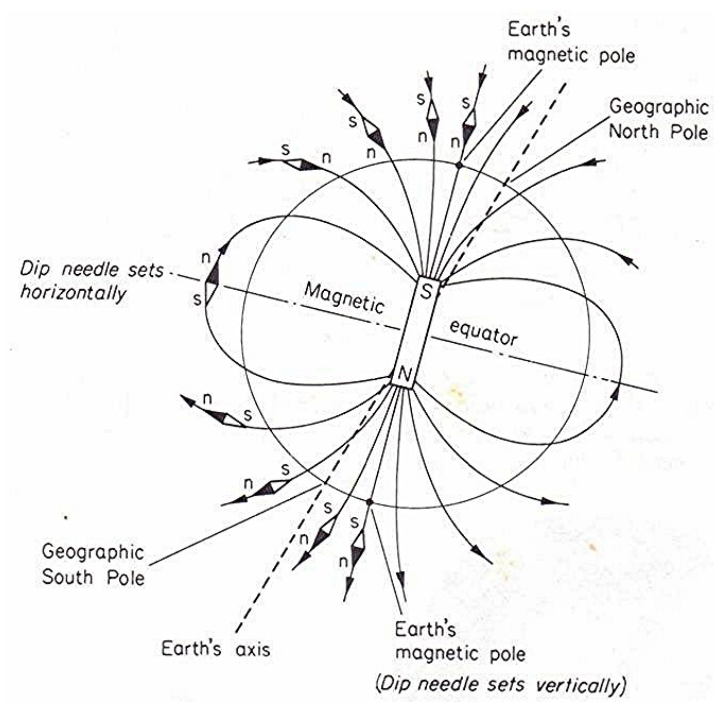

Figure 4 Geomagnetic Dip Angle (source: PhysicsMax.com)

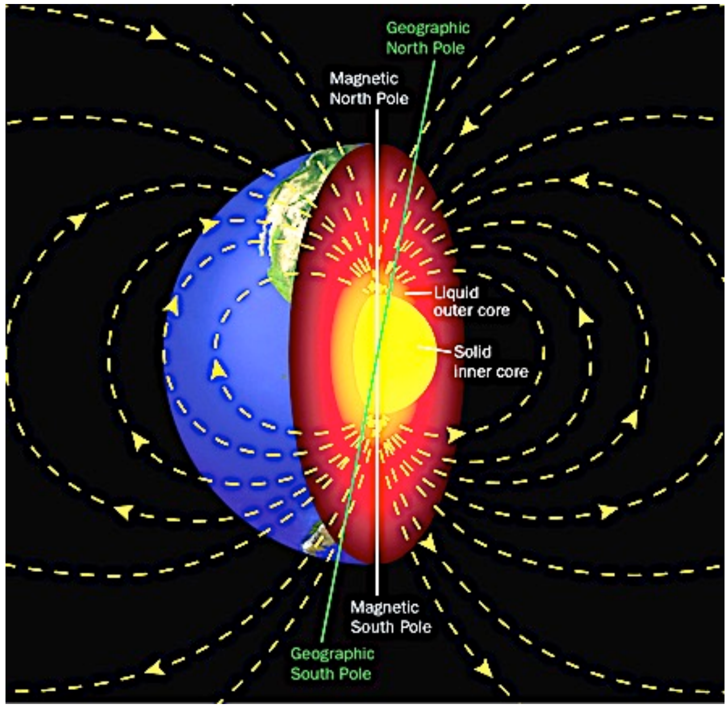

Figure 5 Source of Earth's Magnetic Field (source: Quora)

12.2 Low Latitude Equatorial Electrojet

During the day, as the Sun warms Earth's equatorial atmosphere, temperature and pressure differences develop creating upper atmosphere winds blowing eastward in the E and F regions of the ionosphere. In the equatorial E region, at an altitude of roughly 90 to 130 km, the electron and ion densities are very high due to intense solar ionization. Neutral particle densities at this altitude are also high. In addition, along the magnetic dip equator Earth's magnetic field is horizontal (parallel to Earth's surface) and pointed northward. This set of conditions combine to produce a very strong eastward electrical current, known as the Equatorial Electrojet, flowing within the E region of the equatorial ionosphere.

12.2.1 Eastward Electric Field

The wind generates an electric field in the wispy ionosphere plasma. The plasma is blown along with the wind. However, motion of the large heavy ions is impeded by constant collisions with equally large and heavy neutral air particles while tiny electrons move with considerable freedom. A charge separation develops between the free moving electrons and relatively immobile ions producing a horizontal equatorial electric field $\overrightarrow{E_{eq}}$ pointing east. The magnitude of the electric field builds until equilibrium is reached between the force of the wind driving electrons eastward and the force of the electric field pulling the electrons in the opposite direction.

12.2.2 Crossed Electric and Magnetic Fields

To understand what happens next, we have to examine the movement of a charged particle in the presence of perpendicular electric and magnetic fields.

The force $\overrightarrow{F_E}$ on a charged particle q in an electric field $\vec{E}$ is

$$\overrightarrow{F_E} = q\vec{E}$$

pointed in the same direction as the electric field.

The force $\overrightarrow{F_B}$ on a charged particle q moving with a velocity $\vec{v}$ in a magnetic field $\vec{B}$ is

$$\overrightarrow{F_B} = q\vec{v} \times \vec{B}$$

$$F_B = qvB \sin\theta$$

where θ is the angle between the $\vec{v}\ and\ \vec{B}$ vectors.

The force $\overrightarrow{F_B}$ is perpendicular to the velocity $\vec{v}$ and magnetic field $\vec{B}$ in accordance with the right hand rule shown in Figure 6. In the figure the first vector **"a"** corresponds to the velocity vector $\vec{v}$ and the second vector "b" corresponds to the magnetic field vector $\vec{B}$. The resulting force vector $\overrightarrow{F_B} = q\vec{v} \times \vec{B}$ is represented by "**a** x **b**" in the figure.

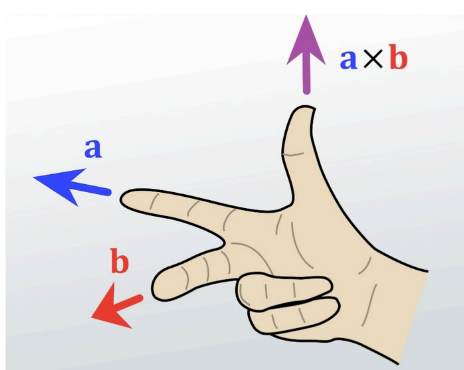

Figure 6 Right hand rule (source: study.com)

A particle q feels the force due to the magnetic field only if the particle is moving with a velocity of $\vec{v}$. The particle will not feel the magnetic field if the particle is stationary relative to the field or traveling in the same direction parallel to the magnetic field ($\theta = 0$). Consequently, a particle in non-parallel motion spirals around a magnetic field in a helical path as shown in Figure 7.

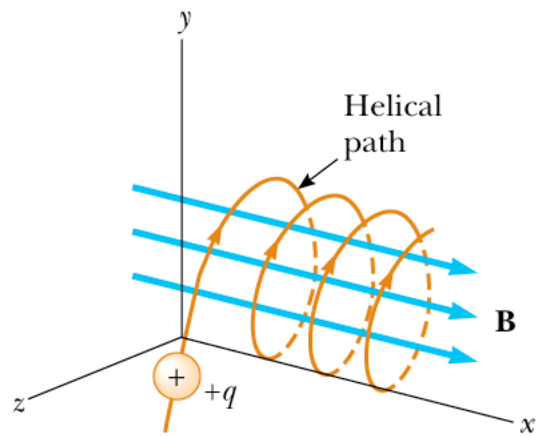

Figure 7 Charged particle spiraling around a magnetic field (source: physexams.com)

A positively charged particle spirals counter clock-wise when looking in the direction of the magnetic field as illustrated in Figure 7. A negative particle spirals clock-wise around the magnetic field lines.

The particle's frequency of gyration around the magnetic field is

$$f = \frac{q}{2\pi m} B \quad Hz$$

where

f = frequency in Hertz

q = electrical charge of the particle in coulombs

m = mass of the particle in kilograms

B = magnetic field strength in Teslas

Consequently, the frequency of gyration increases as the magnetic field strength increases.

The distance r at which the charged particle spirals around the magnetic field is given by

$$r = \frac{mv}{Bq}$$

where

r = distance in meters of the charged particle from the magnetic field line about which it is gyrating

v = velocity of the charged particle in meters per second.

Notice that the distance r, or radius, of a spiraling particle increases with velocity v and decreases with increasing magnetic field strength.

The total force $\overrightarrow{F_L}$ on a charged particle q moving with a velocity $\vec{v}$ when both an electric field $\vec{E}$ magnetic field $\vec{B}$ are present is given by Lorentz's Force Law

$$\overrightarrow{F_L} = q\vec{E} + q\vec{v} \times \vec{B}$$

The equation of motion for the particle is

$$\overrightarrow{F_L} = m\vec{a} = m\frac{d\vec{v}}{dt} = q\vec{E} + q\vec{v} \times \vec{B}$$

where

$\overrightarrow{F_L}$ = Lorentz force
m = mass of charged particle
$\vec{a}$ = acceleration of charged particle
$\vec{v}$ = velocity of charged particle
q = electrical charge on the particle
t = time
$\vec{E}$ = electric field strength
$\vec{B}$ = magnetic field strength

Along the dip equator, the horizontal equatorial electric field $\overrightarrow{E_{eq}}$, produced by the high altitude winds, points eastward while the Earth's magnetic $\overrightarrow{B_0}$, which is also horizontal at the dip equator, points north. That is, both fields are horizontal and perpendicular.

A free electron in the equatorial E region of the ionosphere is accelerated westward by the electric field $\overrightarrow{E_{eq}}$ giving the electron a westward velocity. The electron feels the magnetic field $\overrightarrow{B_0}$ the instant that it starts to move. The magnetic field causes the electron to begin spiraling clockwise around the magnetic field while at the same time the electric field tries to drive the electron westward. The electron's motion from that point on is controlled by the Lorentz equation of motion

$$\overrightarrow{F_L} = m\frac{d\vec{v}}{dt} = q\overrightarrow{E_{eq}} + q\vec{v} \times \overrightarrow{B_0}$$

The faster the electron moves (the higher its velocity v) the larger the radius r of its curved path around a magnetic field line according to

$$r = \frac{mv}{Bq}$$

The curving path of the electron around a magnetic field line eventually causes the electron to move in a direction opposite of the electric field. In this part of its orbit the oppositely directed electric field slows the electron down causing the radius of curvature to get smaller. The electric field accelerates the electron again as the electron rotates back in the direction of the electric field, and the radius of curvature gets larger. The effect of these competing motions is that the net motion of the electron is perpendicular to both of the two fields. Specifically, the drift velocity $\overrightarrow{v_d}$ of an electron in horizontal crossed electric and magnetic fields is

$$\overrightarrow{v_d} = \frac{\overrightarrow{E_{eq}} \times \overrightarrow{B_0}}{|B_0|^2}$$

In accordance with the right hand rule, the electron drifts upward.

For completeness, we need to ask what the motion of a positively charged particle is in the presence of horizontal crossed electric and magnetic fields?

The difference between a negative charge and a positive charge is that

- A negative charge (an electron) is accelerated in the opposite direction of the E field and gyrates around the B field in the clockwise direction.

- A positive charge (an ion) is accelerated in the same direction as the E field and gyrates around the B field in the counter clockwise direction.

The result is that the direction of v_d , illustrated in Figure 8, is the same for both a positive and negative charge!

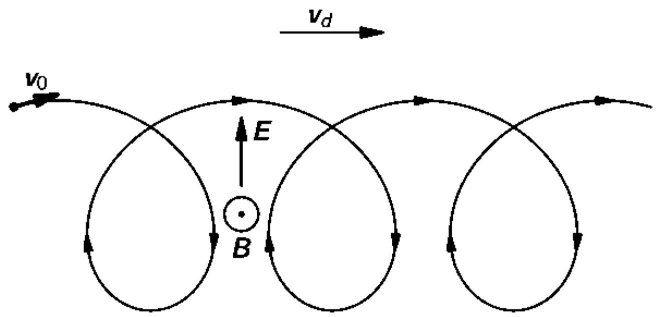

Figure 8 Motion of a charged particle in crossed electric and magnetic fields (source: California Institute of Technology, Michael A. Gottlieb, and Rudolf Pfeiffer)

12.2.3 Equatorial Electrojet Formation

Over the dip equator a vertical charge separation occurs in the E region of the ionosphere as electrons, driven by $\overrightarrow{E_{eq}} \times \overrightarrow{B_0}$ fields, drift upward while positive ions, inhibited by collisions with neutral particles, remain in place. The charge separation, with electrons along the upper boundary of the E region and positive ions at the bottom, creates a vertical electrical field $\overrightarrow{E_h}$. The electric field builds in strength until equilibrium is reached between the downward force on the electrons created by the $\overrightarrow{E_h}$ field and the upward force produced by the $\overrightarrow{E_{eq}} \times \overrightarrow{B_0}$ fields.

Since $\overrightarrow{E_h}$ is also perpendicular to the horizontal northward $\overrightarrow{B_0}$ field, electrons drift westward in accordance with

$$\overrightarrow{v_{EJ}} = \frac{\overrightarrow{E_h} \times \overrightarrow{B_0}}{|B_0|^2}$$

and the right hand rule. The magnitude of E_h is approximately 20 times greater than E_{eq} at an altitude of 110 km (in the middle of the ionosphere's E region) meaning that the westward flow of electrons is considerable. Using conventional current flow, negative electrons traveling westward corresponds to a conventional electrical current composed of positive charge carriers flowing east. This strong eastward electrical current is the Equatorial Electrojet.

The conditions producing the Equatorial Electrojet occur only during daylight hours in a narrow zone approximately 600 km in width above the magnetic dip equator as illustrated in Figure 9. The electrojet is most intense around local noon. All electrical currents produce magnetic fields. The magnetic field produced by the electrojet induces significant diurnal variations in the horizontal surface component of the geomagnetic field in the vicinity of the dip equator.

Figure 9 Low latitude electrojet (source: gfz-potsdam.de)

12.3 Low Latitude Sporadic E zones

At low latitudes, ionization irregularities resulting from the electrojet are believed to be responsible for creating equatorial sporadic E zones. Equatorial sporadic E is essentially a daytime phenomenon with little seasonal variation.

12.4 Spread F Irregularities

Signal scattering due to field-aligned irregularities in electron densities results in an F region phenomena known as spread F, illustrated in Figure 10. Spread F is often noticed in the echoes of ionogram pulses. In some cases, the echoed pulse is up to 10 times wider than the transmitted pulse. This type of distortion is known as **range spread**. In other cases, **frequency spread** distorts critical frequencies so that they are no longer single frequencies but instead a bands of frequencies.

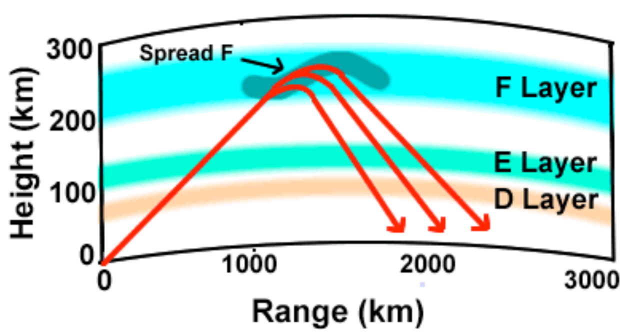

Figure 10 Spread F irregularity (source: www.met.nps.edu)

Spread F is important because it causes radio signals to be seriously distorted, limiting the data rate of signals that can be successfully transmitted. In addition, spread F produces high fading rates.

The field aligned irregularities producing spread F are highly variable in size. They can range from roughly a 100 km to several thousand kilometers wide and about a kilometer thick.

In the equatorial region spread F irregularities appear mainly at night, during magnetically quiet days, in a zone straddling the geomagnetic equator from approximately 20^o south to 20^o north latitude. They begin appearing near sunset, in conjunction with the nightly upward drifting F region, peak around midnight, and then generally decrease. Spread F can occur at any time but tends to be more intense and more numerous at solar maximum, during the equinoxes, and on most nights from November through January. Equatorial spread F disappears with the onset of a magnetic storm.

12.5 Equatorial Plasma Fountain

Collisions occur infrequently in the rarified atmosphere of the equatorial F region. At this altitude both ions and electrons are mobile drifting upward during the day across geomagnetic field lines at a velocity of

$$\overrightarrow{v_d} = \frac{\overrightarrow{E_{eq}} \times \overrightarrow{B_0}}{|B_0|^2}$$

due to the force exerted by horizontal crossed electric and magnetic fields. The electric field gradually weakens and finally disappears at an altitude of around 800 km. With the electric field no longer present, charged particles, both ions and electrons, travel under the influence of gravity and pressure gradients along magnetic field lines curving back to Earth as illustrated in Figure 11. The charged particles eventually reenter the mid part of the F region approximately 15 to 20 degrees either side of the magnetic dip equator. Charged particles transported from the equator combine with those already in the region creating a peak or crest in electron concentrations 15 to 20^o north and south of the magnetic equator. The outflow of particles reduces the electron density along the dip equator producing an equatorial trough. This phenomena is known as the Equatorial Plasma Fountain.

The plasma fountain is usually not symmetric about the magnetic equator. High altitude winds tend to push plasma from the summer to the winter hemisphere. Consequently, the largest electron peaks generally occur in the winter hemisphere. Also, the declination of Earth's magnetic field causes the characteristics of electron peaks to change with geographic longitude.

The plasma fountain crests are most pronounced during solar maximum. However, the average latitudinal locations of the crests vary by only 2^o to 3^o from solar minimum to solar maximum.

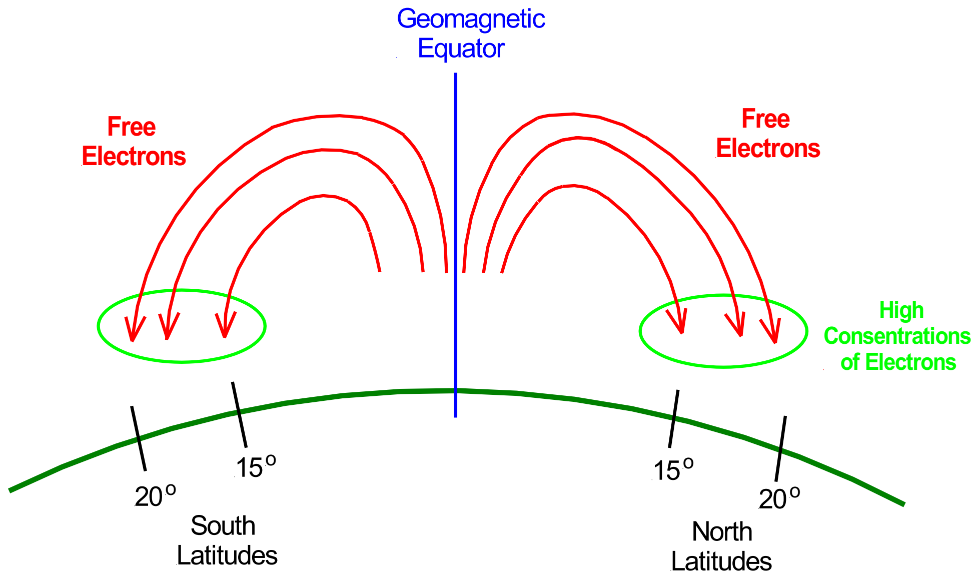

Figure 11 Equatorial plasma fountain (source: author)

12.6 Appleton equatorial anomaly

Initially, before the fountain effect was understood, the high concentration of electrons appearing at latitudes between 15 to 20 degrees was known as the equatorial or Appleton anomaly. It was believed to be an anomaly since the highest electron concentrations were expected to occur over the equator.

The fountain effect is clearly visible in the F2 region winter (December) ionospheric map shown in Figure 12. The black line sloping through South America is the magnetic dip equator. The crests in electron concentrations are the bright pink zones on both sides of the magnetic equator.

The crests usually form in the late afternoon and early evening. While the crests vary from day-to-day and seasonally, they are most pronounced during solar maximum. Notice in Figure 12 that the largest electron peaks (two of them) occur in the winter hemisphere.

F2 critical frequencies within the crests can often reach 15 MHz or higher during solar maximum. In contrast, critical frequencies along the magnetic equator trough will typically be several MHz less.

The altitude at which the F2 peak electron density occurs is also different between the equator and the crests, however, in this case the difference is reversed. The peak F2 electron density along the equator is higher in altitude than the corresponding peak in the crests.

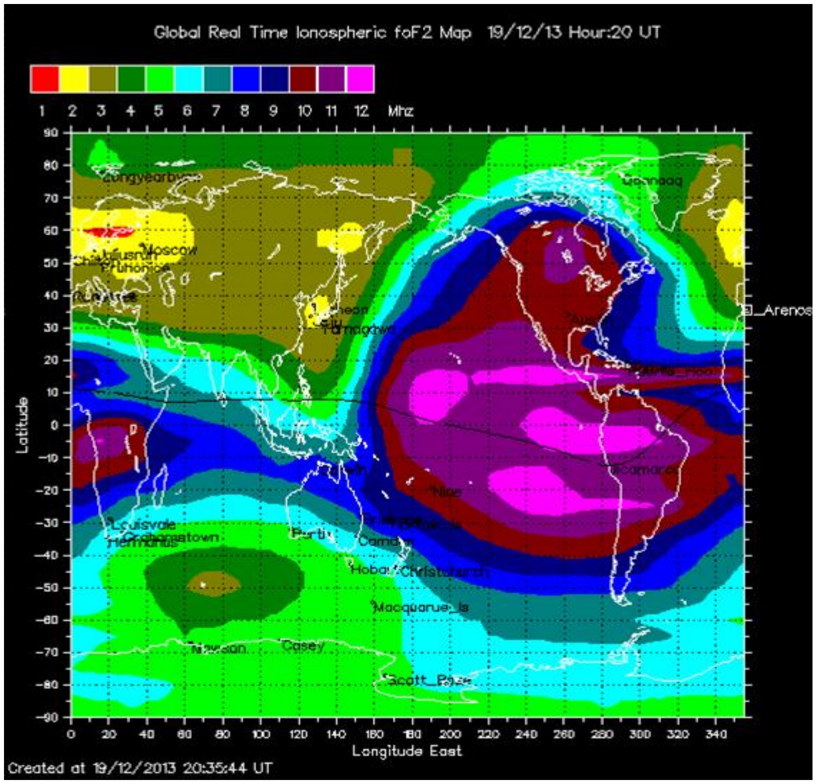

Figure 12 Ionospheric map showing fountain crests (source: Australian Space Weather Services)

The fountain effect distorts the general form of the ionosphere throughout the low latitude equatorial region leading to the interesting transequatorial HF propagation phenomena illustrated in Figure13. Typically, a radio signal transmitted from one hemisphere to the other requires multiple hops through the ionosphere to reach its destination, with signal attenuations occurring with each hop. Instead, a radio signal experiencing transequatorial propagation reflects off one anomaly crest, travels across the equator to the second crest, and then refracts back to Earth. Transequatorial propagation allows a radio signal to traversing the distance from transmitter to receiver in one hop minimizing signal loss.

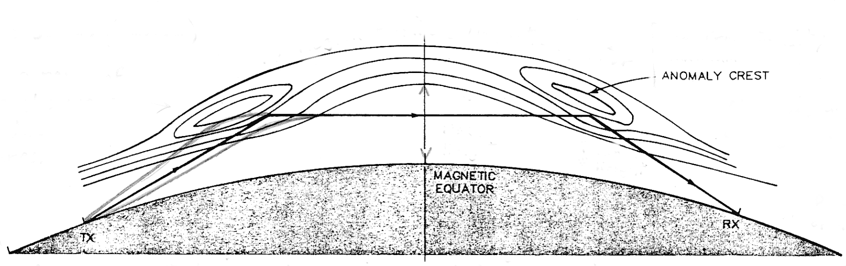

Figure 13 Transequatorial propagation (source: McNamara)

References

Hunsucker R. D.; Hargreaves, J. K.; “The High-Latitude Ionosphere and its Effects on Radio Propagation”; Cambridge University Press 2003

Davies, Kenneth; “Ionospheric Radio”; Peter Peregrinus Ltd.,1990

McNamara, Leo F.; “The Ionosphere: Communications, Surveillance, and Direction Finding”; Krieger Publishing Company, 1991

Bridgman, Tom; “PlasmaZoo: E-cross-B Drift”; NASA Visualizations, https://svs.gsfc.nasa.gov/4265 ; February 2, 2015

Casey, John P; “Overview of the Equatorial Electrojet and Related Ionospheric Current Systems”; NUWC-NPT Technical Report 11, 676 25 April 2005

Pitkanen, Timo; “Dynamics Of The Polar Cap Boundary And The Auroral Oval In The Nightside Ionosphere”; Department of Physics University of Oulu, Finland, June 2011

Nichols, Eric P.; “Propagation and Radio Science”; The American Radio Relay League, Inc. 2015

Yeang, Chen-Pang; “Probing The Sky With Radio Waves”; The University of Chicago Press, 2013

Devoldere, John; “Low-Band DXing” fourth edition; ARRL, 2005

Levis, Curt A. ; Johnson, Joel T.; and Teixeira, Fernando L.; “Radiowave Propagation Physics and Applications”; John Wiley & Sons, Inc., 2010

Ahrens, C. Donald; “Essentials of Meteorology”; Wadsworth Publishing Company, 1998

UCAR Center for Science Education (UCAR SciEd); https://scied.ucar.edu/learning-zone/atmosphere/

Khazanov, George V.; “Space Weather Fundamentals”; CRC Press, 2016

Foukal, Peter; “Solar Astrophysics third edition”; Whiley-VCH Publishing Company, 2013

Ganushkina, N. Yu.; Liemohn, M. W.; Dubyagin. S.; “Current Systems in the Earth’s Magnetosphere”; AGU, March 8, 2018

Gallagher, Dr. D.L.; “The Earth’s Plasmasphere”; Space Plasma Physics, Marshall Space Flight Center, Huntsville, Al, September 05, 2018

Moore, T. E., Morwitz, J. L.; “Stellar Ablation of Planetary Atmospheres”; August 9, 2007

Yau, Andrew W.; Abe, Takumi; Peterson, W. K.; “The Polar Wind: recent Observations”; Department of Physics and Astronomy, University of Calgary

Carroll, Bradley W. and Ostlie, Dale A.; “An Introduction to Modern Astrophysics”; Addison-Wesley Publishing Company Inc., 1996

Goodman, John M.; “Space Weather & Telecommunications”; Springer Science+Business Media Inc. 2005

Cander, Ljiljana R.; “Ionospheric Space Weather”; Springer Nature Switzerland AG 2019

Moldwin, Mark; “An Introduction to Space Weather”; Cambridge University Press, 2008

Campbell, Wallace H.; “Introduction to Geomagnetic Fields”; Cambridge University Press, 2003

Golub, Leon and Pasachoff, Jay M.; “Nearest Star The Surprising Science of Our Sun second edition”; Cambridge University Press, 2014

Loff, Sarah: ”Explorer and Early Satellites”; National Aeronautics and Space Administration, Aug 3, 2017

Minzner, R. A.; “The 1976 Standard Atmosphere Above 86 km Altitude” NASA Goddard Space Flight Center, 1976