The Equatorial Ionosphere: A Tutorial

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Outline of presentation

This paper reviews
✓ The Ionosphere
✓ Equatorial Ionosphere
✓ Equatorial Ionospheric Anomaly
✓ Equatorial Plasma Fountain
✓ Equatorial Electrojet
✓ Available resources
✓ Are you here?
The Ionosphere
The Ionosphere

- Upper part of the earth’s atmosphere where electrons exist in sufficient proportion as to affect the propagation of radio waves

- 50 km – 1000 km
The Ionosphere

- Upper part of the atmosphere where electrons and charged particles exist in sufficient proportion as to affect the propagation of radio waves
- It extends from about 50 km above the surface of the Earth and terminates at the thermosphere
- It is appropriately named the ionosphere because it consists of several layers of electrically charged gas atoms called ions
- The ions are formed by a process called ionization
- It owes its existence primarily to ultraviolet radiation from the sun.
Formation of Ionosphere

✓ At the outer reaches of the Earth's environment, solar radiation strikes the atmosphere with a power density of 1370 Wm$^2$, a value known as the "solar constant."

✓ This intense level of radiation is spread over a broad spectrum ranging from radio frequencies through infrared (IR) radiation and visible light to X-rays

✓ Solar radiation at ultraviolet (UV) and shorter wavelengths is considered to be "ionizing" since photons of energy at these frequencies are capable of dislodging an electron from a neutral gas atom or molecule during a collision
Formation of Ionosphere

Intense Incoming Solar Radiation

Is Partially Absorbed by an Oxygen Atom

Producing an Oxygen Ion And a Free Electron

Oxygen Atom Initially Neutral

Incoming solar radiation is incident on a gas atom (or molecule).

In the process, part of this radiation is absorbed by the atom

....and a free electron and a positively charged ion are produced
Ionospheric Layers

- Atmospheric compositions varies with height
- Solar radiation, acting on the different compositions of the atmosphere with height, generates layers of ionization
- Ionosphere is stratified
Ionospheric layers

Stratified layers
Varying concentration

• D
• E
• F1
• F2 (F1 & F2 combine at night to form single F layer)

Characterizing the ionosphere is of utmost interest due to the numerous complexities associated with the region [Rabiu, et al., 2007]
D layer

- innermost layer, 50 km to 90 km above the Earth’s surface
- Ionization here is due to Lyman series-alpha hydrogen radiation at a wavelength of 121.5 nm ionizing nitric oxide (NO)
- In addition, when the sun is active with 50 or more sunspots, hard X-rays (wavelength < 1 nm) ionize the air (N₂, O₂). During the night cosmic rays produce a residual amount of ionization
- Recombination is high in the D layer, thus the net ionization effect is very low and as a result high-frequency (HF) radio waves are not reflected by the D layer
- The frequency of collision between electrons and other particles in this region during the day is about 10 million collisions per second.
- The D layer is mainly responsible for absorption of HF radio waves, particularly at 10 MHz and below, with progressively smaller absorption as the frequency gets higher.
D layer

- The absorption is small at night and greatest about midday.
- The layer reduces greatly after sunset, but remains due to galactic cosmic rays.
- A common example of the D layer in action is the disappearance of distant AM broadcast band stations in the daytime.
- During solar proton events, ionization can reach unusually high levels in the D-region over the high and polar latitudes.
- Such events are known as Polar Cap Absorption (or PCA) events, because the increased ionization significantly enhances the absorption of radio signals passing through the region.
- In fact, absorption levels can increase by many tens of dB during intense events, which is enough to absorb most (if not all) transpolar HF radio signal transmissions.
- Such events typically last less than 24 to 48 hours.
E layer

- middle layer, 90 km to 120 km above the Earth’s surface
- Ionization is due to soft X-ray (1-10 nm) and far ultraviolet (UV) solar radiation ionization of molecular oxygen ($O_2$)
- Normally this layer can only reflect radio waves having frequencies lower than about 10 MHz and has a negative effect on frequencies above 10 MHz due to its partial absorption of these waves
- However during intense Sporadic E events it can reflect frequencies as high as 250 MHz
- The vertical structure of the E layer is primarily determined by the competing effects of ionization and recombination
- At night the E layer begins to disappear because the primary source of ionization is no longer present.
E layer

- This results in an increase in the height where the layer maximizes because recombination is faster in the lower layers.
- Diurnal changes in the high altitude neutral winds also plays a role.
- The increase in the height of the E layer maximum increases the range to which radio waves can travel by reflection from the layer.
- This region is also known as the Kennelly-Heaviside Layer or simply the Heaviside layer.
- Its existence was predicted in 1902 independently and almost simultaneously by the American electrical engineer Arthur Edwin Kennelly (1861-1939) and the British physicist Oliver Heaviside (1850-1925).
- However, it was not until 1924 that its existence was detected by Edward V. Appleton.
Es layer or sporadic E-layer

• Sporadic E propagation is characterized by small clouds of intense ionization, which can support radio wave reflections from 25 – 225 MHz
• Sporadic-E events may last for just a few minutes to several hours and make radio amateurs very excited, as propagation paths which are generally unreachable, can open up
• There are multiple causes of sporadic-E that are still being pursued by researchers
• This propagation occurs most frequently during the summer months with major occurrences during the summer, and minor occurrences during the winter
Es layer or sporadic E-layer

- During the summer, this mode is popular due to its high signal levels.
- The skip distances are generally around 1000km (620 miles). VHF TV and FM broadcast DX'ers also get excited as their signals can be bounced back to earth by Es.
- Distances for short hop events can be as close as 500 miles or up to 1,400 (or more) for a long, single hop.
- Double-hop reception over 2,000 miles is possible.
F layer

• also known as the Appleton layer, is 120 km to 400 km above the Earth’s surface
• It is the top most layer of the ionosphere
• Here extreme ultraviolet (UV, 10–100 nm) solar radiation ionizes atomic oxygen
• The F layer consists of one layer at night, but in the presence of sunlight (during the day), it divides into two layers, labeled F1 & F2
• These F layers are responsible for most skywave propagation of radio waves, facilitating high frequency (HF, or shortwave) radio communications over long distances
• They are thickest and most effective in refracting radio signals on the side of the earth facing the sun
• From 1972 to 1975 NASA launched the AEROS and AEROS B satellites to study the F region
Techniques for Probing the Ionosphere

- Radio propagation - up to satellite altitudes
- Geomagnetic field studies - altitude > 90 km
- Rocket - up to ionospheric altitudes
- Satellites - up to satellite altitudes
- Radar - up to satellite altitudes
- Lidar - up to satellite altitudes
Equatorial Ionosphere
Magnetic Equator

• Magnetic (dip) equator is defined as the locus of zero dip along the surface of the earth (Cohen, 1967)
• Its latitude varies as a function of latitude
• In the neighbourhood of magnetic equator, there is unusual orientation of the field with relation to the Earth
• Charged particles move more readily along magnetic field lines
• Migration of charged particles along geomagnetic field lines is associated with a two-humped latitudinal distribution of electron density, with minimum at the magnetic equator
Fig. 1. Relative positions of the magnetic and geographic equators
Equatorial Ionosphere

- E layer – Equatorial electrojet
- F layer – Equatorial anomaly, Spread F.
Equatorial Ionospheric Anomaly EIA

- The F2 layer in the vicinity of the magnetic dip equator is characterized by a depression in the ionization density or “trough” at the equator and two humps, one on each side of the equator (at about \(\pm 17^\circ\) magnetic latitude) during the day that lasts for several hours after sunset.

- This interesting phenomenon is called the “equatorial anomaly” or “Appleton anomaly” (Appleton, 1946). The cause of the anomaly is often attributed to the so-called “fountain effect”

- It is the eastward electric field at the equator that gives rise to an upward \(E\times B\) drift during the daytime.

- After the plasma is lifted to greater heights it is able to diffuse downward along magnetic field lines under the influence of gravity and pressure gradient forces.

- The net result is the formation of a plasma “fountain” which produces an enhanced plasma concentration (crest) at higher latitudes and a reduced plasma concentration (trough) at the equator
Equatorial Plasma Fountain

- The daytime dynamo generated eastward electric field combined with the northward geomagnetic field lifts the equatorial ionosphere to 700 km to over one thousand kilometers.

- After losing momentum, the electrons diffuse along the field lines to either side of the equator to form two crests

[Yeh et al 2001]
Equatorial Anomaly Crest

- In response to the diurnal variations of the dynamo electric field [Fejer, 1981], the anomaly crest begins to form around 09:00 LT on a normal day.

- As time progresses, the anomaly crest intensifies and moves with a speed of about 1° per hour to a higher latitude.

[Yeh et al 2001]
Equatorial Anomaly Crest

- This speed is maintained till shortly before noon when the poleward motion is slowed and reversed at around 14:00 LT
- During this time, the anomaly crest is most intense, showing the characteristic tilt, an approximate alignment of its core along the geomagnetic field lines and the asymmetric behavior
- Thereafter, the crest weakens and recedes slowly equatorward.
- On many days the crest is observed to linger into the night with a smaller spread in latitude

[Yeh et al 2001]
EIA & MUF

• The net result is two belts of enhanced plasma density parallel to the magnetic equator maximising at about f 15” latitude.

• These high electron densities give rise to unusually high maximum usable frequencies (MUF) on communication paths which cross the equator, particularly in the afternoon.
Scintillations in Equatorial Region

✓ Ionospheric scintillations are rapid and temporal fluctuations in the amplitude and phase of transionospheric radio signals resulting from electron density irregularities in the ionosphere.

✓ EIA - responsible for the formation of the plasma density irregularities that give rise to scintillations.
Equatorial Spread F ESF

✓ Irregularities in the equatorial F-region have been studied for decades
✓ Abundant ionospheric density irregularities in equatorial ionosphere
✓ These ionospheric irregularities are well known as equatorial spread-F (ESF) according to a nomenclature introduced after the appearance of spread echoes on ionograms.
✓ The term ‘spread-F irregularities’ is synonymous with electron density fluctuations or structures on scales ranging from a few tens of centimeters to several hundred kilometers.
Image of equatorial "arcs" and ionospheric irregularities over Africa, a spectacular example of space weather in the region. The image was obtained by the GUVI instrument on the TIMED satellite using the emissions at 135.6 nm from the recombination of O\(^+\) ions with electrons. The increased airglow emission maps the equatorial ionization anomaly or "arcs," and the depletions within each arc that arise from the Rayleigh-Taylor instability.

The observations from GUVI cover about 2000 km in each swath - the swath boundaries can be seen as the "dashed" regions that run from the left hand corner to the right hand corner. The brighter regions depicting the equatorial arcs follow the magnetic equator (indicated as a sinusoidal dotted line offset from the geographic equator).
Equatorial Electrojet

• The E (dynamo) region of the equatorial ionosphere consists of 2 layers of currents responsible for the quiet solar daily variations in Earth’s magnetic field:

• Worldwide solar quiet daily variation, WSq (altitude 118 ± 7 km), responsible for the global quiet daily variation observed in the earth’s magnetic field.

• Equatorial electrojet, EEJ - an intense current flowing eastward in the low latitude ionosphere within the narrow region flanking the dip equator (altitude 106 ± 2 km) (Chapman, 1951, Onwumechili, 1992)

• Enhanced (Cowling) conductivity associated with the special equatorial magnetic field configuration results in the strong daytime EEJ currents
Manifestations of EEJ

- Spatial structures of its intense current density
- configurations & regular temporal variations of its current system
- magnetic fields of its current system
- the ionospheric plasma density irregularities generated by the turbulent flow of the EEJ current
- the electric fields and ionospheric plasma drifts in the dip equatorial zone
- the quiet counter equatorial electrojet CEJ
- temporal variabilities of the above phenomenon.
Equivalent currents

Note: Worldwide Sq (WSq), EEJ & AEJ

Source: Goddard Space Flight Center (NASA/GSFC) and the Danish Space Research Institute (DSRI).
Mid-latitude troughs

AE?

EEJ?

Latitudinal variation of Annual Sq 1996

(Rabiu et al, 2006)
Resources
Probing the Ionosphere

• Radio propagation - up to satellite altitudes
• Geomagnetic field studies - altitude > 90 km
• Rocket - up to ionospheric altitudes
• Satellites - up to satellite altitudes
• Radar - up to satellite altitudes
• Lidar - up to satellite altitudes
Radio propagation

✓ Ground based measurements
  • Transmitters at one end and receiver at another end.
  • Tx and Rx are separated by distances corresponding to the space region being monitored.

✓ Satellite-Earth communication
  • Signals from satellite are received and studied at the earth based stations.
Geomagnetic field studies

• Magnetometers are used in studying the Earth’s magnetic field
• Ground magnetometers
• Airborne magnetometers
• Satellite bound magnetometers
• Rocket borne magnetometers
MAGDAS at ILORIN, Nigeria. August 2006
Rocket borne equipments

• A rocket is a vehicle, missile or aircraft which obtains thrust by the reaction to the ejection of fast moving fluid from within a rocket engine.

• Rockets are used for fireworks, weaponry, launching artificial satellites, human spaceflight and exploring other planets.

• While they are inefficient for low speed, they can reach extremely high speeds when staging is employed.

• They are made to carry the required payload.
Rocket borne equipments

• A **rocket** is a **vehicle**, **missile** or **aircraft** which obtains **thrust** by the **reaction** to the ejection of fast moving **fluid** from within a **rocket engine**.

• Rockets are used for **fireworks**, weaponry, launching artificial **satellites**, **human spaceflight** and **exploring** other planets.

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Satellite Technique

- Instruments for measuring atmospheric and interstellar parameters are placed on board as payloads on specific satellites.
Geomagnetic Data Capture Systems

GROUND OBSERVATORIES  MAGSAT  POGO  OERSTED  CHAMP  SWARM
The CHAMP satellite was launched in July 2000 at 450 km altitude in a near-circular orbit with an inclination of 87.3°.

The physical parameters of the CHAMP satellite are:
- Total Mass 522 kg
- Height 0.750 m
- Length (with 4.044 m Boom) 8.333 m
- Width 1.621 m
- Area to Mass Ratio 0.00138 m²kg⁻¹
Ground Geomagnetic Observations

Dated back to Chinese 300 BC (Campbel 1997)

Organised (Modern) Observations:
- IGY – e.g. Addis, Ibadan
- IEEY
- INTERMAGNET
- CPMN/ MAGDAS
IEEY Observatories 1992-1994

After Mazaudier 2007
MAGDAS/CPMN
(MAGnetic Data Acquisition System/Circump-pan Pacific Magnetometer Network)

courtesy - K. Yumoto SERC
Are you here?

• **What is the Ionosphere**

• Upper part of the atmosphere where electrons and charged particles exist in sufficient proportion as to affect the propagation of radio waves

• **Mention the layers of the ionosphere from bottom**
  
  – D, E, F1 and F2

• **What is magnetic equator**
  
  – the locus of zero dip along the surface of the earth

• **What distinguished the equatorial ionosphere from other latitudes**
  
  – The configuration of magnetic field lines, enhanced cowling conductivity
Are you here?

• In equatorial anomaly region, what happened to plasma after it is lifted to certain heights?

• It is able to diffuse downward along magnetic field lines under the influence of gravity and pressure gradient forces. The net result is the formation of a plasma “fountain” which produces an enhanced plasma concentration (crest) at higher latitudes and a reduced plasma concentration (trough) at the equator.

• What is Equatorial electrojet EEJ

• EEJ is the intense ionospheric current flowing eastwards within the narrow strip flanking the dip equator, responsible for the observed enhanced horizontal magnetic field intensity at the magnetic equatorial neighbourhood.
THANK YOU