Theory of HF radars and Ionosondes

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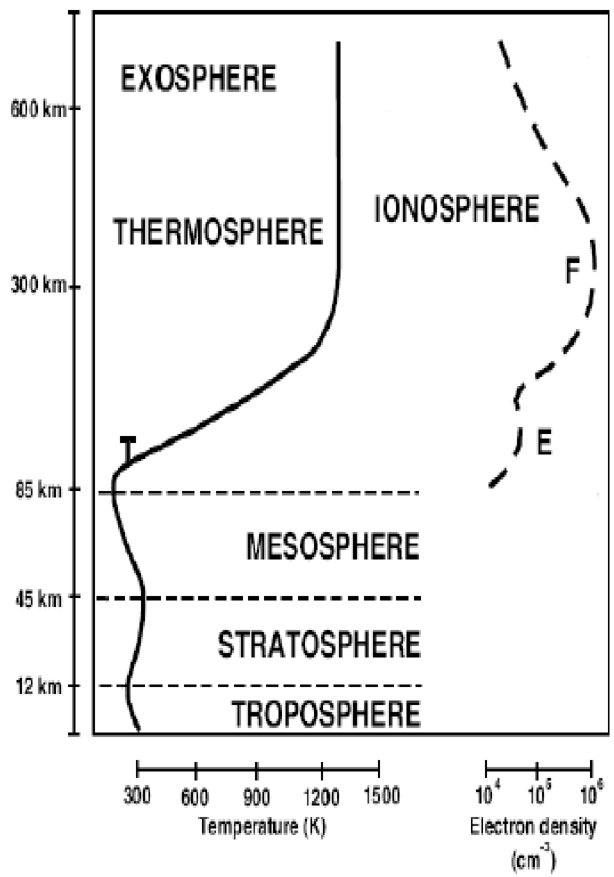
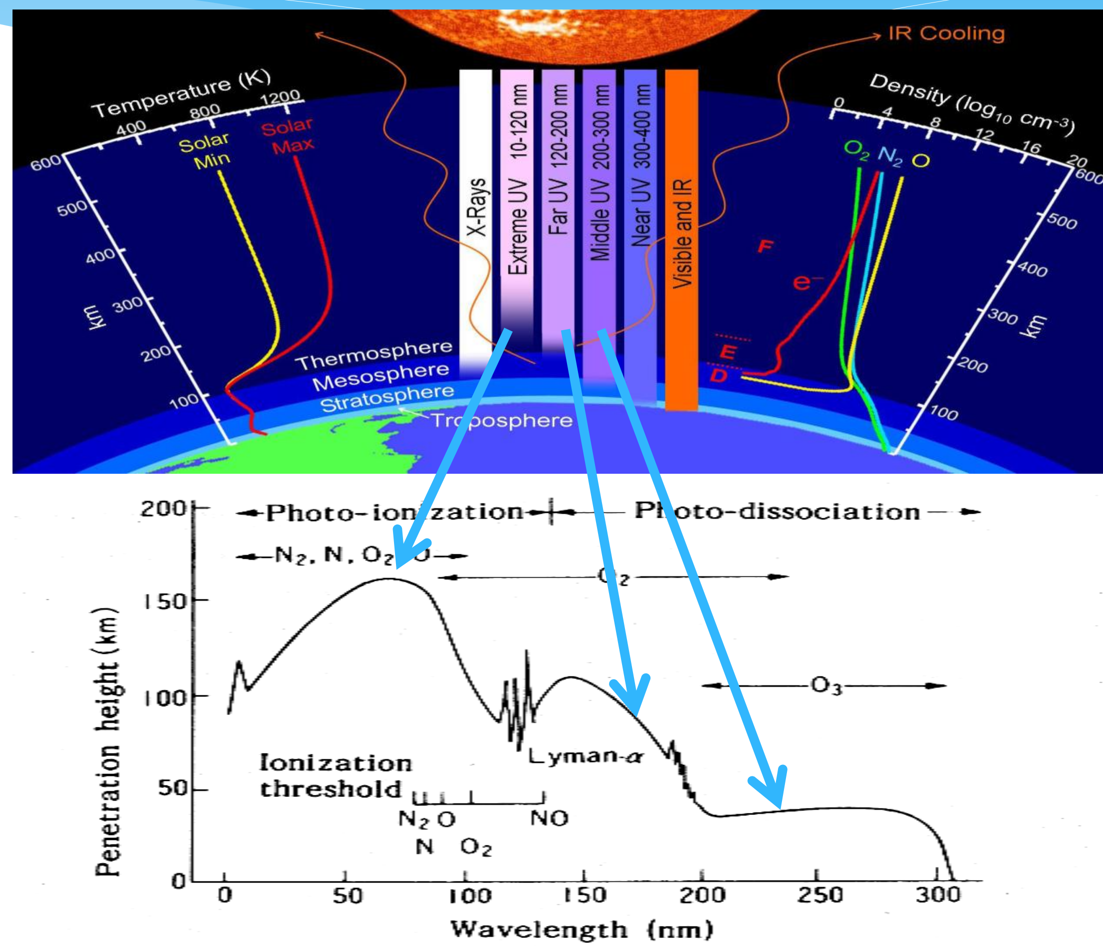
Outline

* Ionosphere: Formation and important application
* Methods of ionospheric studies
* RADAR: Principle and technique
* IONOSONDE: Ionospheric RADAR
* Ionosonde technique
* Application of Ionosonde in Ionospheric studies

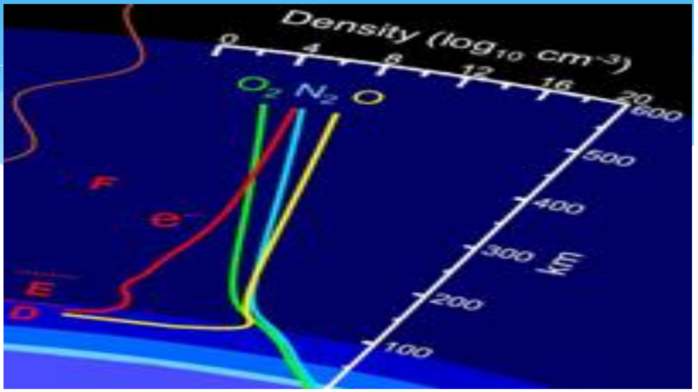
Ionosphere: Formation and Important Applications (1 of 8)





Ionosphere: Formation and Important Applications (2 of 8)

Ionization production depends on two factors:



1. Concentration of neutrals

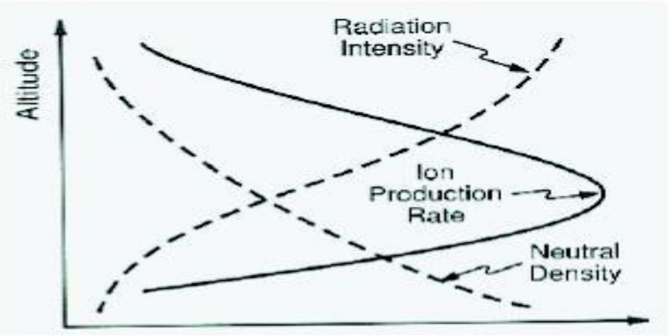
$$n_n(z) = n_0 \exp(-z/H) \quad \ldots.1$$

2. Intensity of radiation reaching the layer

$$I(z) = I_\infty \exp\left[-\frac{\sigma_\nu n_0 H}{\cos\chi_\nu}\exp(-z/H)\right] \quad \ldots.2$$

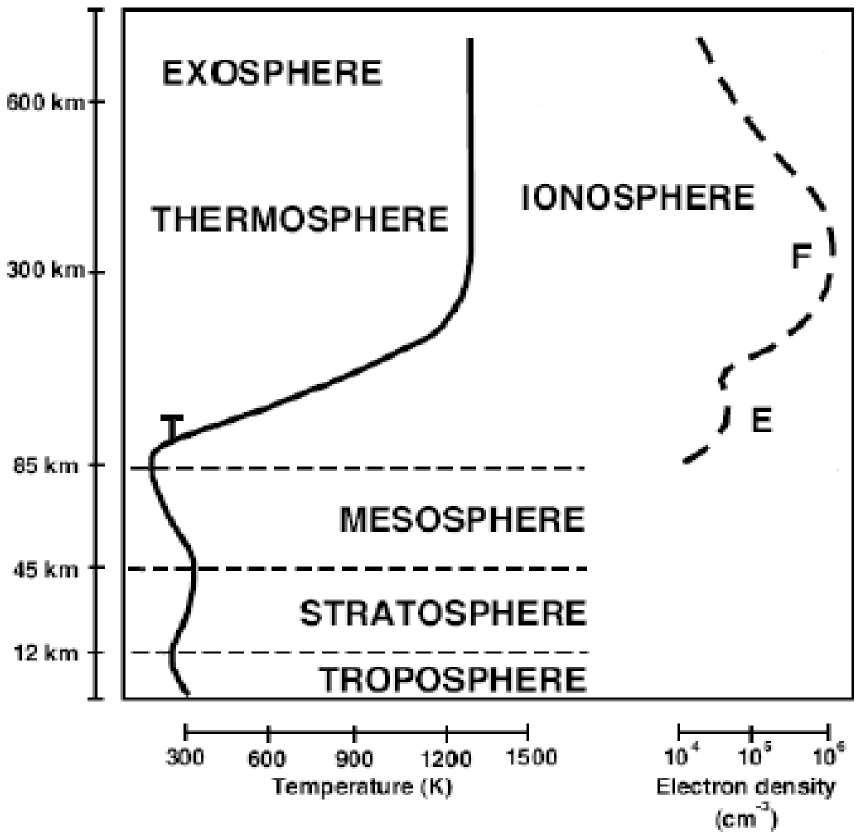
Ionization production rate is thus given as:

$$q_\nu(z) = \kappa_\nu \sigma_\nu n_0 I_\infty \exp\left[-\frac{z}{H} - \frac{\sigma_\nu n_0 H}{\cos\chi_\nu}\exp(-z/H)\right] \quad \ldots..3$$



Ionization production peaks at an altitude midway between the 60 and 500 km

Ionosphere and Important Applications (3 of 8)



The result: Chapman Layer

$$\frac{dn_e}{dt} = q_{v,j} - \propto_D n^2 \qquad \ldots\ldots(4)$$

Chapman Layer is based on the theory which assumes:

- A monocroma1c ionizing radia1on from the sun,
- A single neutral constituent to be ionized distributed exponen1ally (i.e., with a constant scale height),
- Photochemical equilibrium i.e. $n_e = n_i$

Ionosphere: Formation and Important Applications (4 of 8)

IONIZATION PROCESSES

Photodissociation $AB + h\nu \rightarrow A + B$

(wavelenght > 130 nm)

Photoexcitation $AB + h\nu \rightarrow AB^{*}$

(wavelenght < 130 nm)

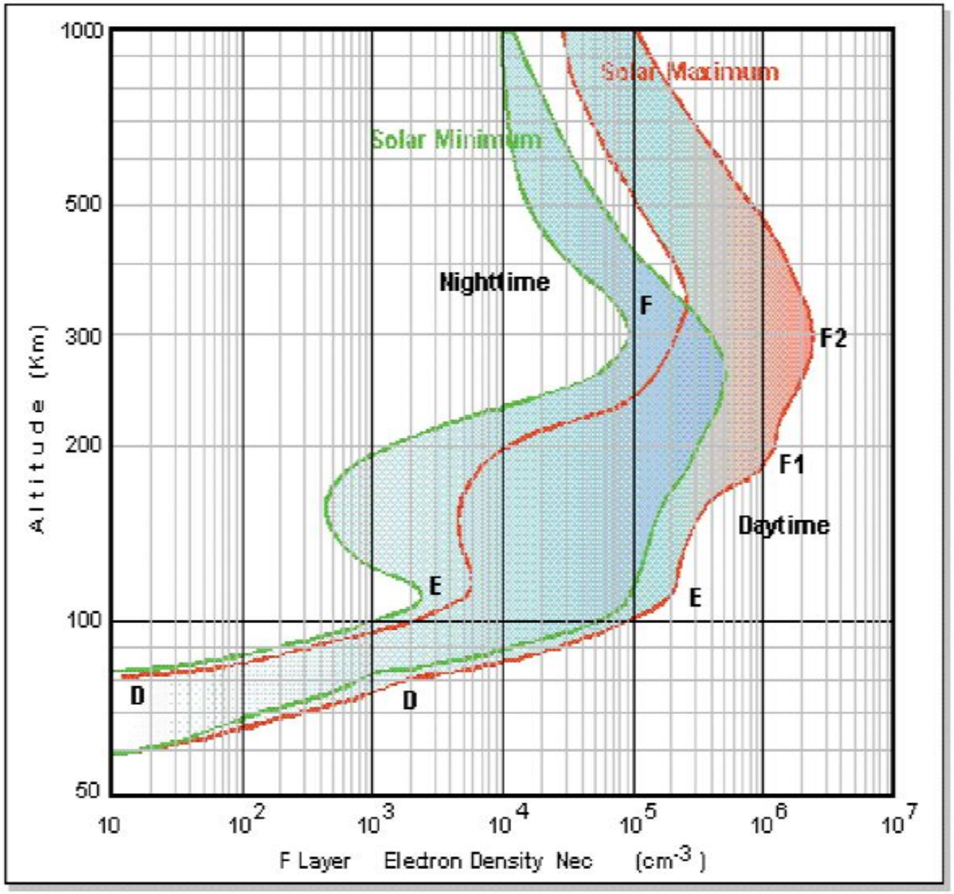
Photoionization $A + h\nu \rightarrow A^{+} + e$

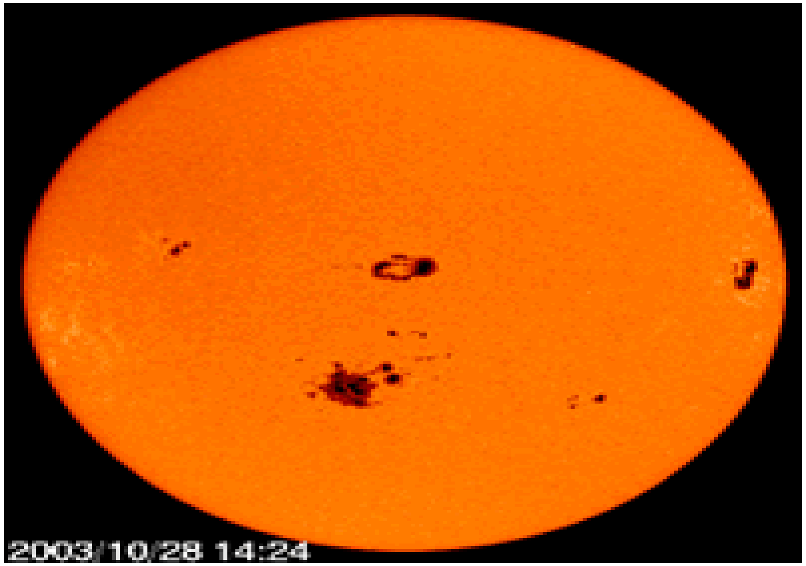
(wavelenght < 100 nm)

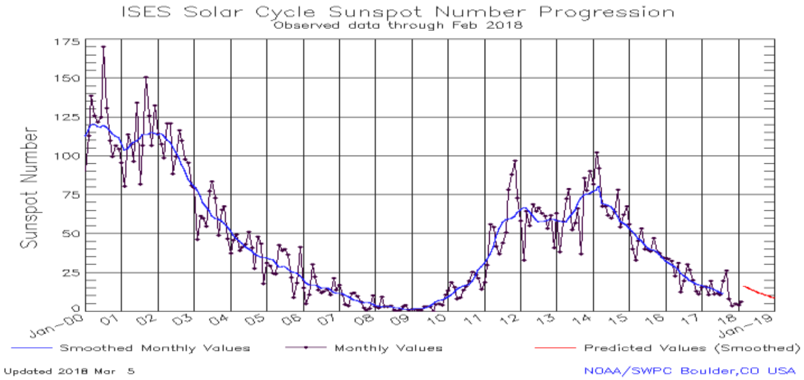
RECOMBINATION PROCESSES

- **Radiative Recombination**
  $$X^{+} + e \rightarrow X + h\nu \; (\alpha_R)$$
- **Dissociative Recombination**
  $$XY^{+} + e \rightarrow X + Y \; (\gamma_D)$$
- **Ion-Ion Recombination**
  $$XY^{+} + Z^{-} \rightarrow neutrals \; (\alpha_l)$$
- **Recombination as a two-stages process**
  $$N^{+}{}_2 + O \rightarrow NO^{+} + N(\gamma)$$
  $$O^{+} + N_2 \rightarrow NO^{+} + N \; (\beta)$$
  $$NO^{+} + e \rightarrow N + O \; (\propto_D)$$

Ionospheric structure is solar dependent: Diurnal, seasonal and 11 year Solar cycle.



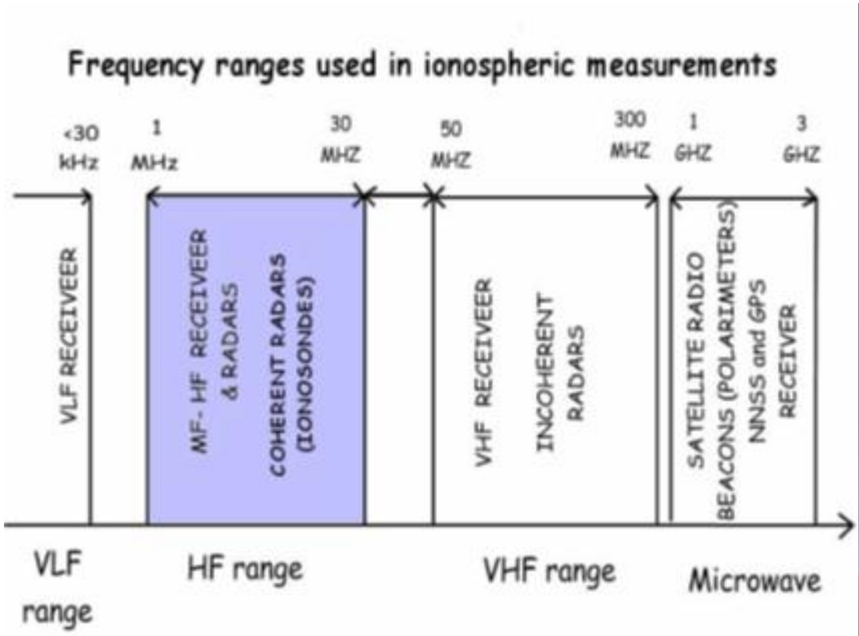


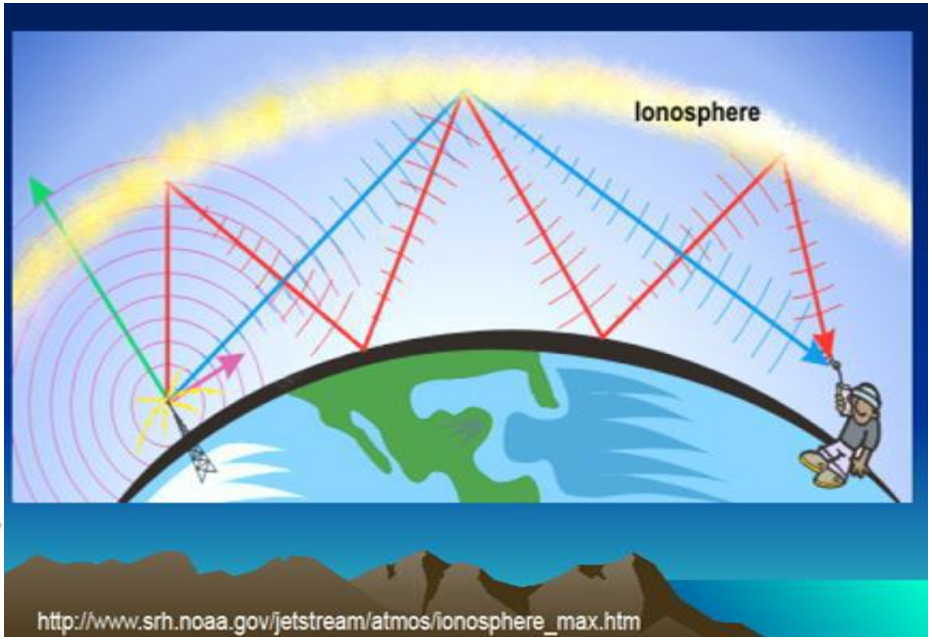


Ionosphere: Formation and Important Applications (6 of 8)

Radio frequency spectrum of the e/m waves

ELF/ Hz	SLF/ Hz	ULF /Hz	VLF/ KHz	LF/ KHz	MF/ KHz	HF/ MHz	VHF/ MHz	UHF/M Hz	SHF/ GHz	EHF /GHZ
3	30	300	3	30	300	3	30	300	3	300
30	300	3	30	300	3 MHz	30	300	3GHz	30	





Ionosphere: Formation and Important Applications (7 of 8)

Layer	Approximate Elevation	Major Component	Importance	When Present
Plasmasphere Topside F	> 1200 km > 450 km	H+ O+	Domain of line of sight HF propagation	Always
F	F1:140 km - 200 km F2:200 km – 450 km	F1:O+, NO+ F2: O+, N+	Main "reflection" region for HF propagation	Always - stronger during daytime
E	90 km - 140 km	O2+, NO+	Lower-frequency "reflection" region	Always - but very weak at night
D	60 km – 90 km	NO+, O2+	Main absorption region	Daytime only

Ionosphere: Formation and important application (8 of 8)

Propagation is dependent on refractive index which in turn depends on the state of the ionosphere as dictated by electron density, collision of particles and presence of magnetic field. Hence there are three possible conditions for propagation:

Case 1: Cold plasma:

$$n^2 = 1 - X = 1 - \frac{f_p^2}{f^2} = 1 - \frac{kN}{f^2}$$

Case 2: plus collision among species:

$$n^2 = 1 - \frac{X}{(1 - jZ)}$$

Case 3: presence of permanent magnetic field:

Magneto-ionic equation or Appleton-Hartee equation.

$$n^2 = 1 - \frac{X}{(1 - jz) + \left\{ \frac{-Y_x^2}{2(1 - X - jz)} \mp \left[\left(\frac{Y_x^4}{4(1 - X - jz)^2} \right) + Y_z^2 \right]^{1/2} \right\}}$$

$$\bar{Y} = \frac{e\bar{B}}{m\omega}, \quad X = \frac{Ne^2}{\varepsilon_0 m\omega^2}, \quad z = \frac{\nu}{\omega}$$

Methods of Ionospheric Studies (1/7)

Remote-sensing methods

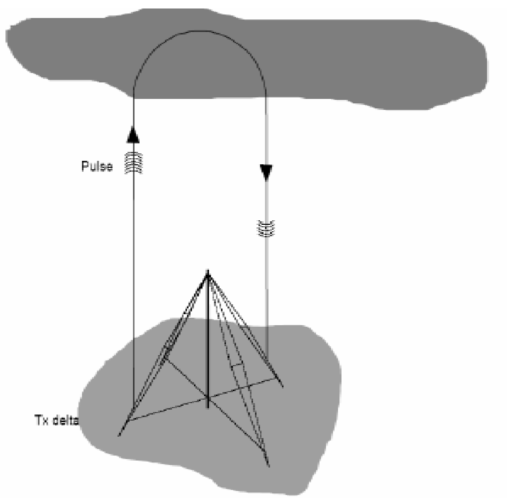
- GNSS: GPS, GLONASS, Galileo, BeiDou
- RADARs
- Magnetometers
- Air sky glow imager

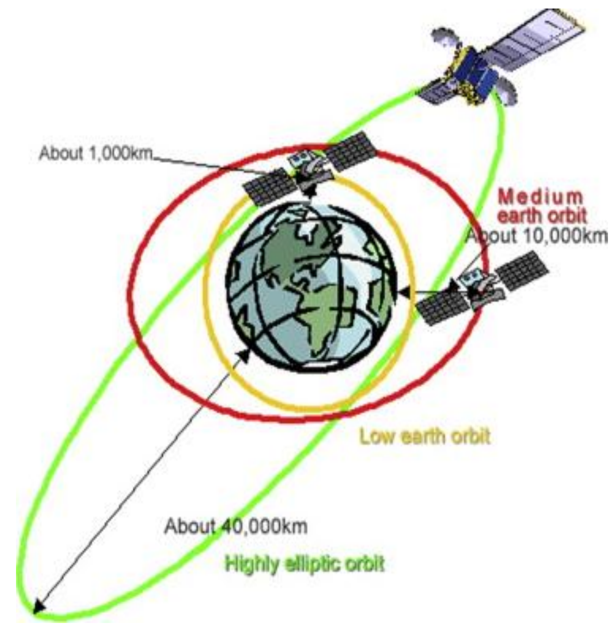
In-situ methods

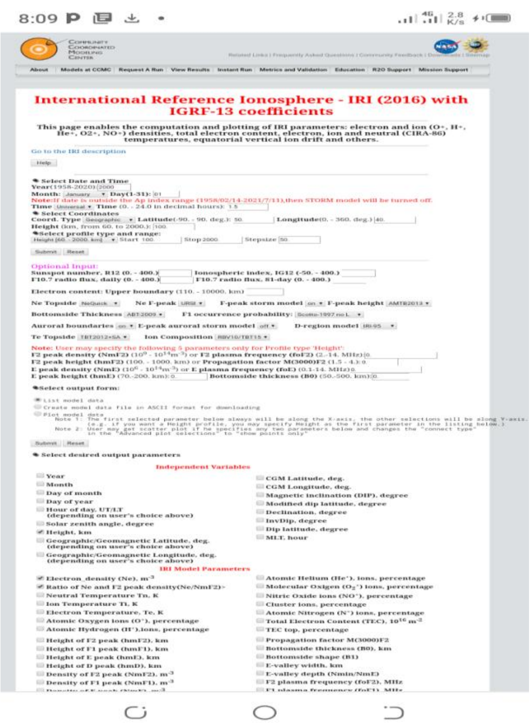
-Radio Occultation technique
-Low Earth Orbit Satellites
-Dual Frequency Altimeter e.g. TOPEX-Poseidon,
Beacons

Models

-IRI group of models
-NeQuick1 & 2
-IRI-Plas
- AfriTEC

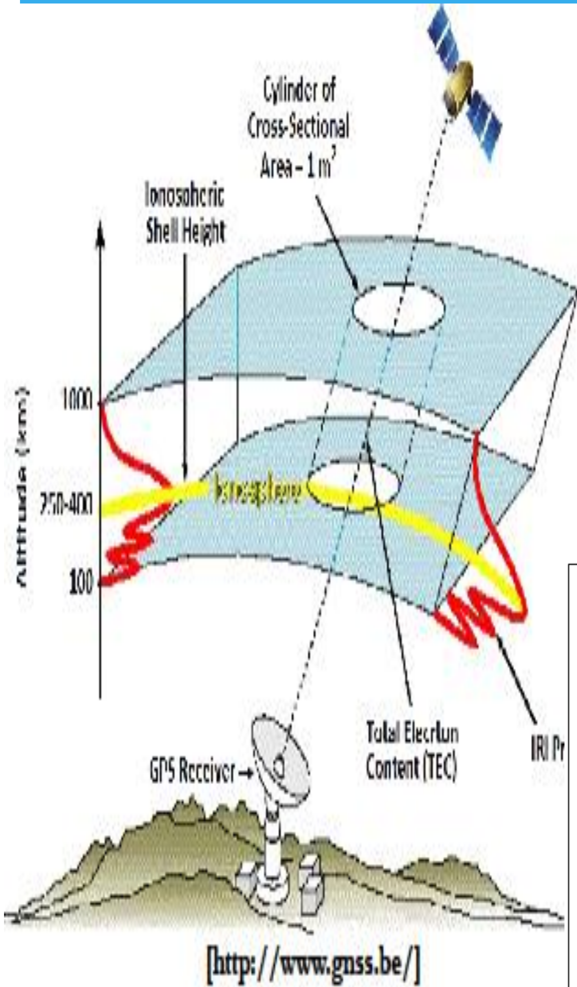


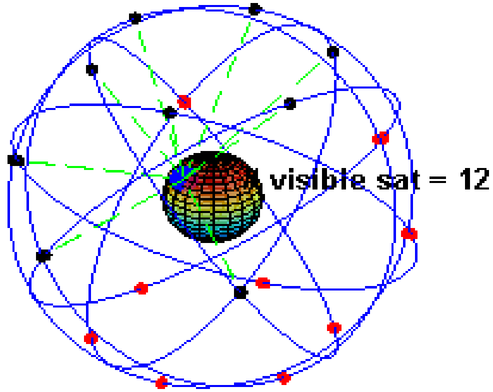




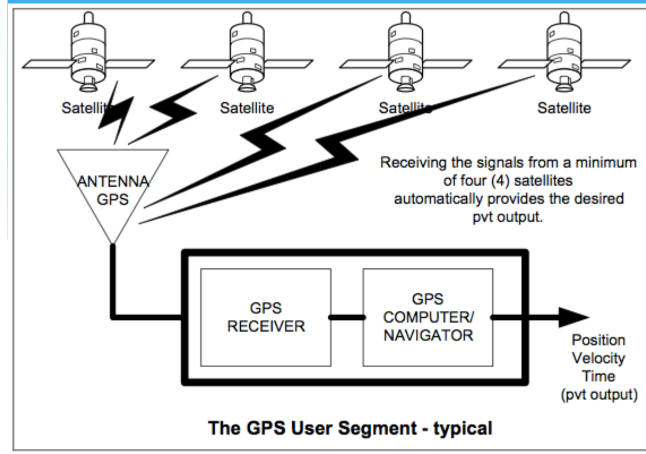
Methods of ionospheric studies: GNSS (2/7)

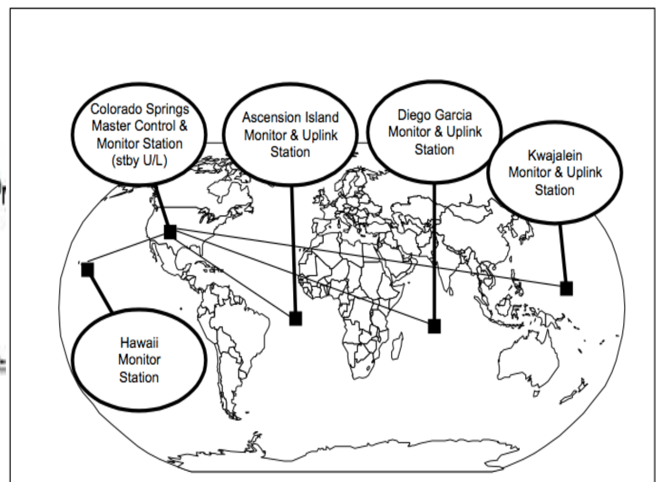
Principle



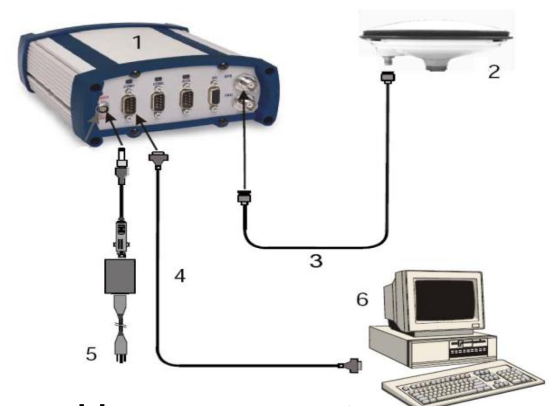


24 Satellite constellation in medium orbit – space segment





GPS Ground Segment



User segment

Methods of ionospheric studies: Radars (Ionosondes) (3/7)

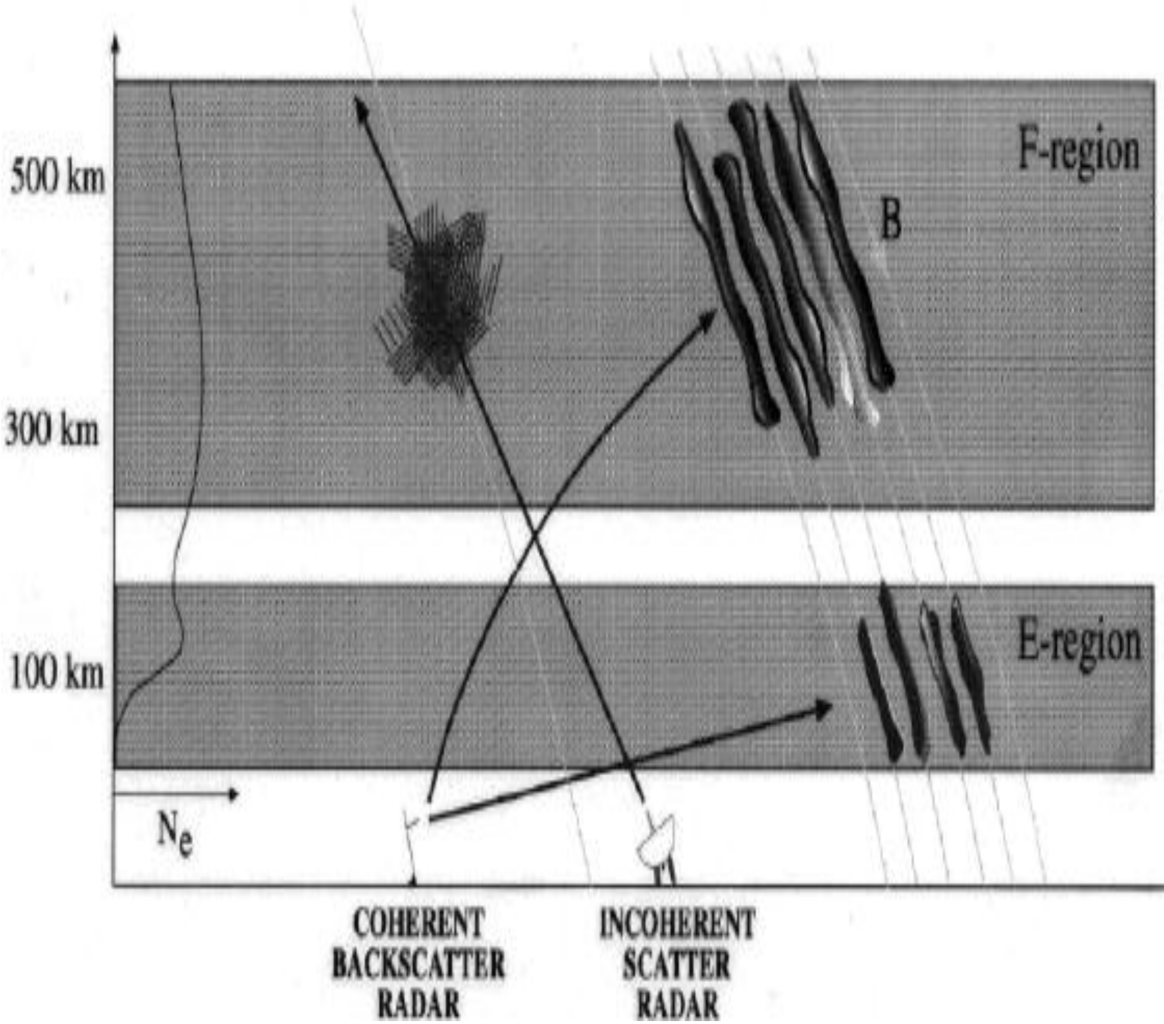
Transmitting Antenna

The Sounder

Receiving Antenna

Ionospheric studies: Radar

(Coherent and Incoherent Scatter radar) (4/7)



They use refraction to bend the rays so as to hit perpendicularity to the magnetic field, B in the E and F region

Ionospheric studies: Radar

(Coherent and Incoherent Scatter radar) (5/7)

Key properties

Differences:

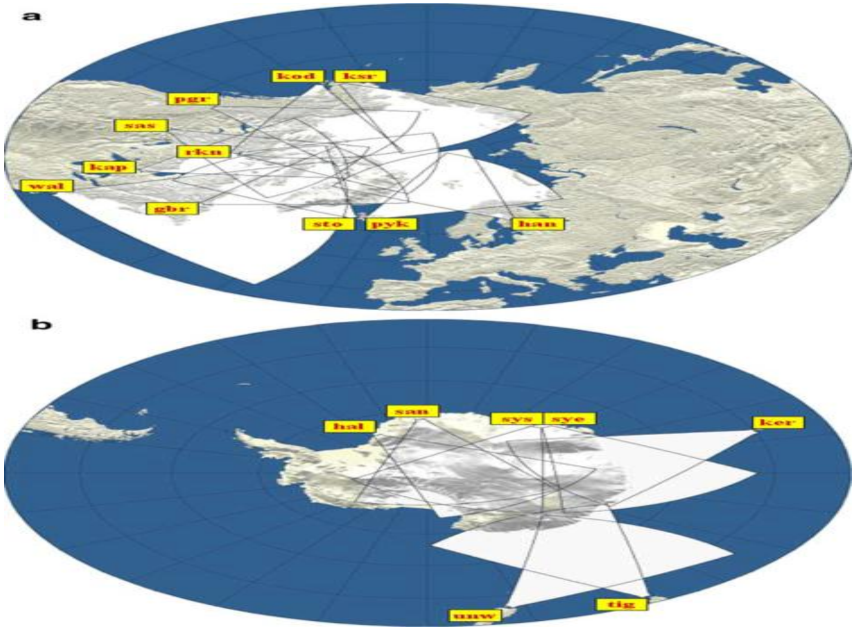
- **Echoes for both radars come from collective scattering, or plasma irregularities.**
- **Incoherent scatter radars see weak ion-acoustic structures in any direction**
- **Coherent scatter radars only see large amplitude structures aligned with the magnetic field.**

Radar	Incoherent	Coherent
Power	~1 MW	~10h kW
Frequency	Fixed (UHF/VHF)	Variable (HF)
Range resolution	100’s m -10s km	15-45 km
Temporal resolution	ms	Mins
Field of View	Narrow	Wide
Parameters	Ne, Te, Ti, Vi	Vi, power, spectral width
Radar	Coded pulses	Multi-pulse

Ionospheric studies: Radar (SuperDARN) (6/7)

Super Dual Auroral Radar Network (SuperDARN)

- network of high-frequency (HF) radars
- located in the high- and mid-latitude regions of both hemispheres
- to study the dynamics of the ionosphere and upper atmosphere on global scales
- as of 01 Jan 2018, there were a total of 36 SuperDARN radars:
- 23 in the Northern Hemisphere and 13 in the Southern Hemisphere (Nishitani et al., 2019)



Fields of view of the SuperDARN radars in the northern (a) and southern (b) hemispheres. (Chisham et al., 2007)

Ionospheric studies: All-sky Airglow Imager (7/7)

Typical configuration of an imaging system

Front lens
(narrow, all-sky)

Optical system
(lenses, filters)

Detector (TV, film, CCD)

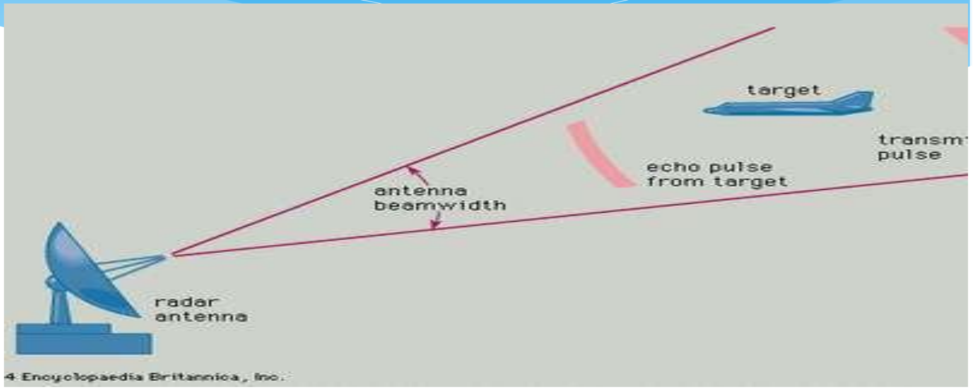
(Courtesy: **Martinis, 2009)**

Radar: Principle and technique (1/7)

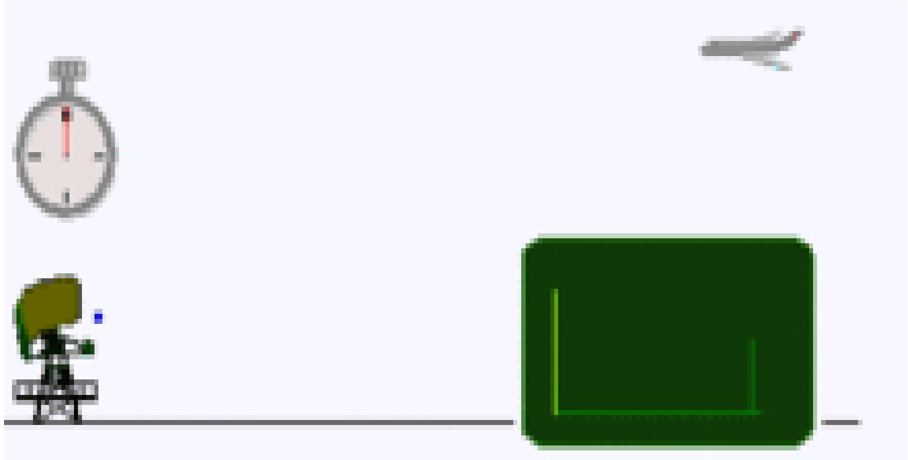
Radar

- acronym for **Radio Detection And Ranging**, coined by the US Navy in 1940.
- **developed** and used during the second world war to detect the approach of hostile aircraft (**Niraj and GeethaPriya, 2017**)
- an electromagnetic (wireless technology) detection system that uses radio waves to detect the direction, speed, shape, range and other characteristics of distant objects
- Its use dates back to 20th century
- detection of aircraft, ships, spacecraft, guided missile, motor vehicles, ocean circulation, spillage, marine navigation etc.
- **COMPOSITION:**

transmitter, transmitting antenna, receiving antenna, receiver, and **processor.**



Radio waves from the transmitter reflect off the object and return to the receiver, giving information about the object's location and speed



Radar: Principle and technique (2/7)

Radar Principle:

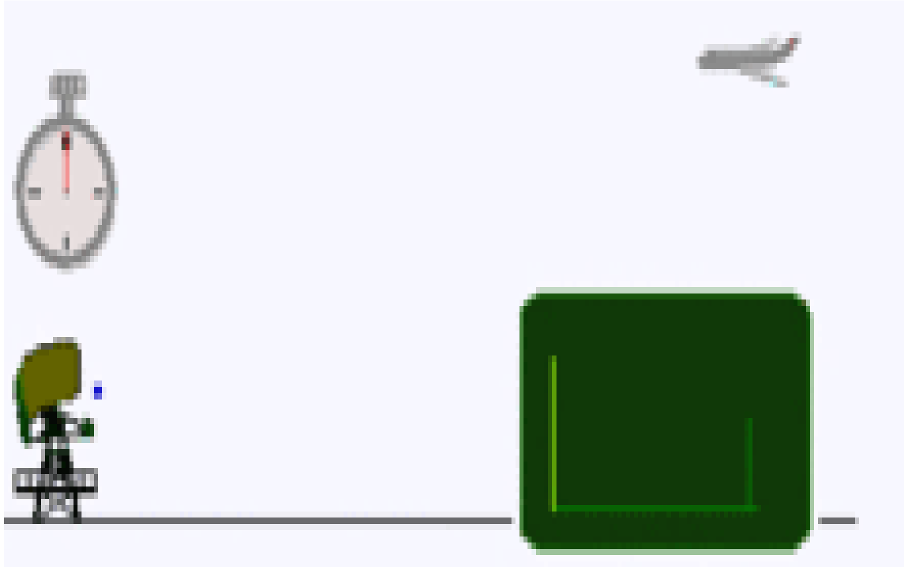
- The **transmitter** transmits radio signal through the **transmitting antenna** in all the directions.
- The target object intercept radio signal and reflect back in all the directions.
- Some of the reflected signal is received by the **receiver** through the **receiving antenna**.
- The received signal is processed further by the **processor** through digital signal processing and amplification
- a decision is made at the reception output for determining the presence of reflected signal from the target.

Basic Theory:

Timing of the delay between a transmitted pulse of radio energy and its subsequent return. Range is obtained:

$$Range = c\frac{\Delta t}{2}$$

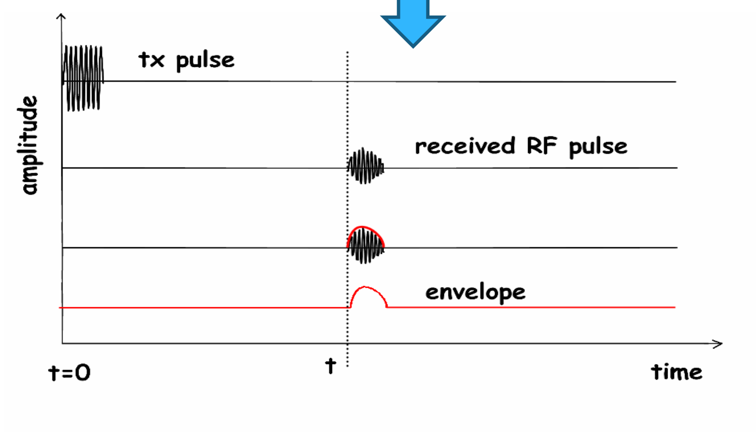
where Δt is duration of the returned signal, c = 3 x 10^8 m/s, the speed of light at which all electromagnetic waves propagate.



Radar: Principle and technique (3/7)

Envelope technique.

- The receiver follows the relative maxima of the signal and then
- generates an electric signal that "envelopes" the received echo.



According to this simple model we can derive the main features of an envelope radar:

Target distance is $D = c\frac{\Delta t}{2}$

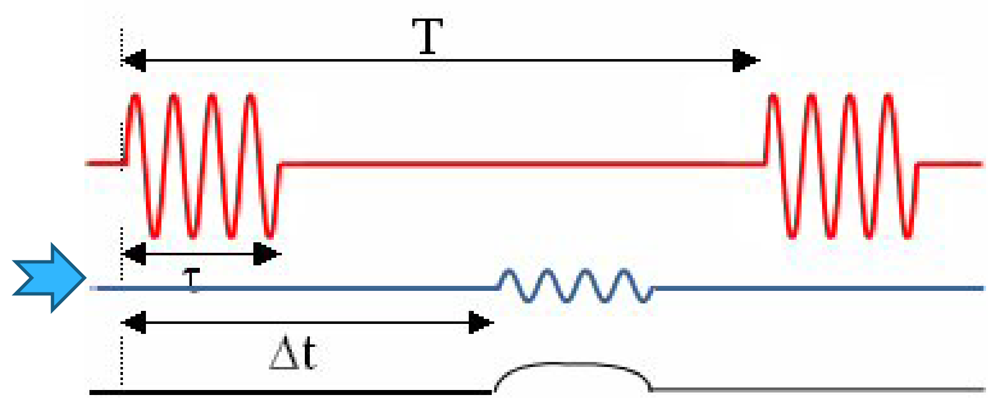
while the

Minimum distance is $D_{min} = c\frac{\tau}{2}$

•Using the envelope technique:

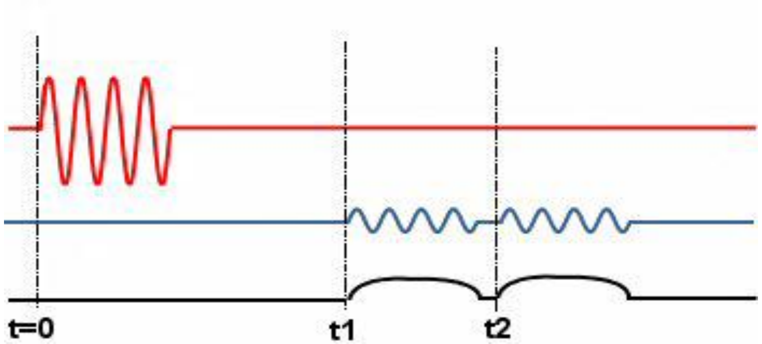
- Pulses of length equal to τ seconds repeated every T seconds are emitted through a transmitting antenna.

- the receiving system generates a pulse whose length is approximately τ.



Radar: Principle and technique (4/7)

Evaluation of radar's resolution is achieved by distinguishing between the time of arrival of 2 echoes if the arriving times are such that $t_2 - t_1 > t$



Minimum distance between 2 targets (spatial resolution)

$$\delta D = c\frac{\tau}{2}$$

Maximum target distance

$$D_{max} = c\frac{T}{2}$$

Energy from a P power amplifier

$$E = P.\tau$$

Requirement for transmission and reception:

•The power has to be adequate so that a detectable signal is obtained (design requirement).

•Reflected and attenuated energy from the target must be received through RX antenna after an interval Δt

Advantages

• Very simple TX and RX systems

•There is the possibility of a complete analog receiver (no PC is needed).

Disadvantages

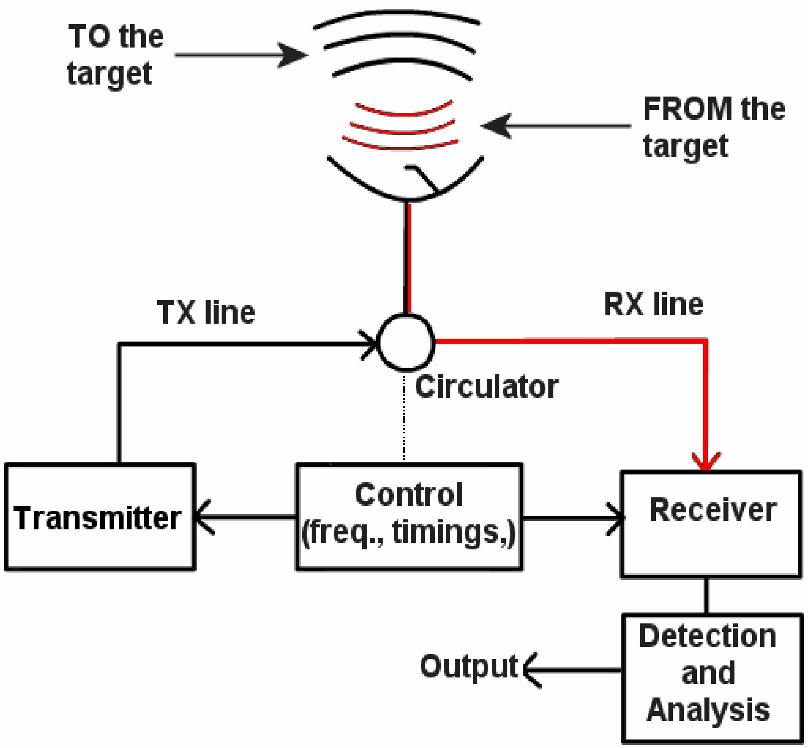
•Compromise for τ is needed.

•Sometimes we have a limited resolution.

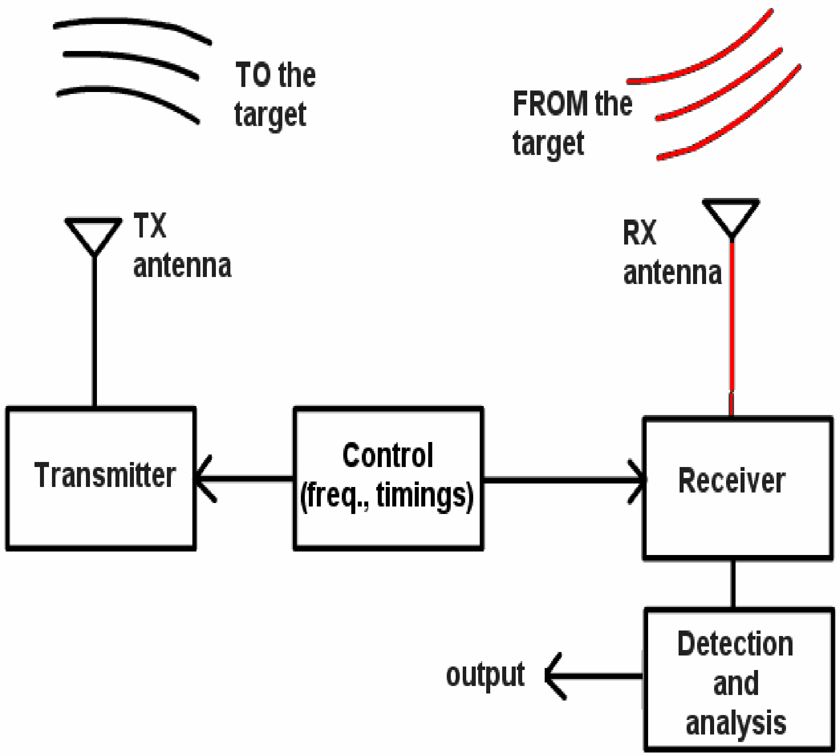
•High power to get a good SNR

Radar: Principle and technique (5/7)

Basic architecture



Monostatic: One antenna



Bistatic: Two antenna system

Radar: Principle and technique (6/7)

Radar Equation:

Power received by receiver,

$$P_r = \frac{\lambda^2 G_T G_r \sigma P_{rad}}{(4\pi)^3 r^4}$$

λ - wavelength of radio signal, $G_T G_r$ - Tx and Rx antenna directive gain, σ - Radar cross section
P_{rad} - emitted power (dissipated in the antenna characteristic impedance) , r- distance between the radar and the target

Radar cross section is the area which is able to catch the incident wave and then scatter the energy in the surrounding space isotropically.

$$\sigma = 4\pi r^2 \frac{P_s}{P_i}$$

Where Ps is the scattered power density at a distance r from the target, Pi is the power density on target.

Radar: Principle and technique (7/7)

Classification of RADAR

- General Pulse RADAR
- Maximum Range Resolution RADAR
- Pulse Compression RADAR
- Continuous Wave RADAR (CWRADAR)
- Frequency Modulated Continuous Wave RADAR (FM-CWRADAR)
- Synthetic Aperture RADAR (SAR)
- Inverse Synthetic Aperture RADAR (ISAR)
- Tracking RADAR
- Weather (meteorology) Observation RADAR
- Imaging RADAR

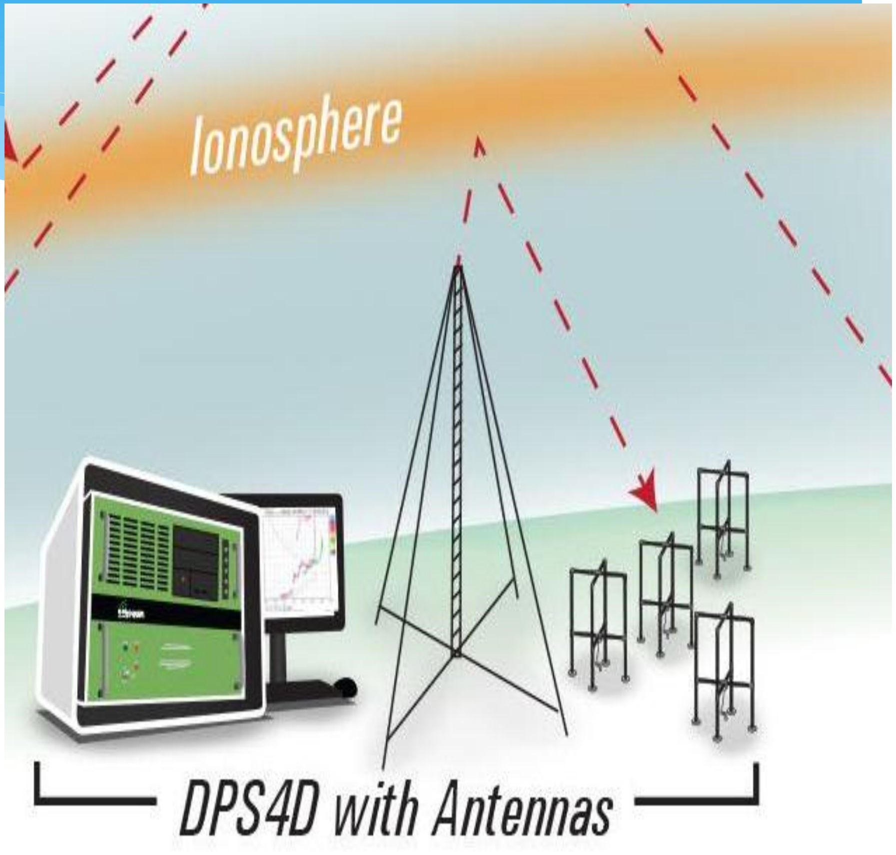
Applications of RADAR

- Air Traffic Control
- Aircraft Navigation
- Ship Navigation and Safety
- Space RADAR
- Remote sensing and Environment
- Law Enforcement
- Military area
- Global Ocean Monitoring
- Experiment Applications
- Microwave Sounder Application
- Win Scatterometer Application
- Land use, Forestry and Agriculture

Ionosonde: Ionospheric RADAR (1/6)

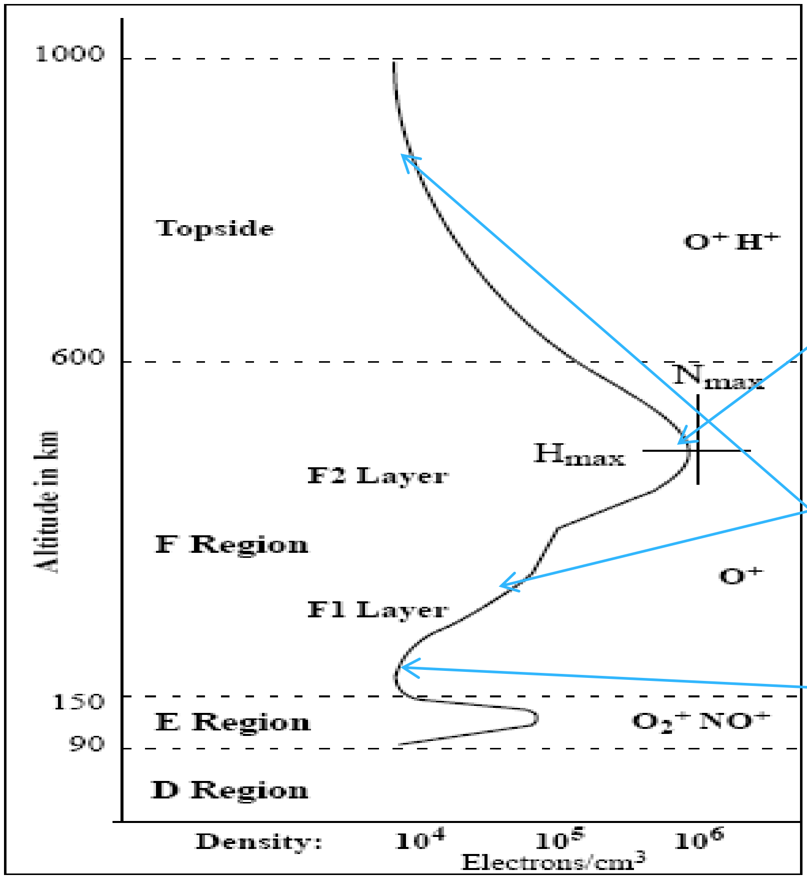
An ionosonde, or chirpsounder, is **a special RADAR** for the examination of the ionosphere.

- **The basic ionosonde technology was invented in 1925 by Gregory Breit and Merle A. Tuve**
- **further developed in the late 1920s by a number of prominent physicists, including Edward Victor Appleton.**



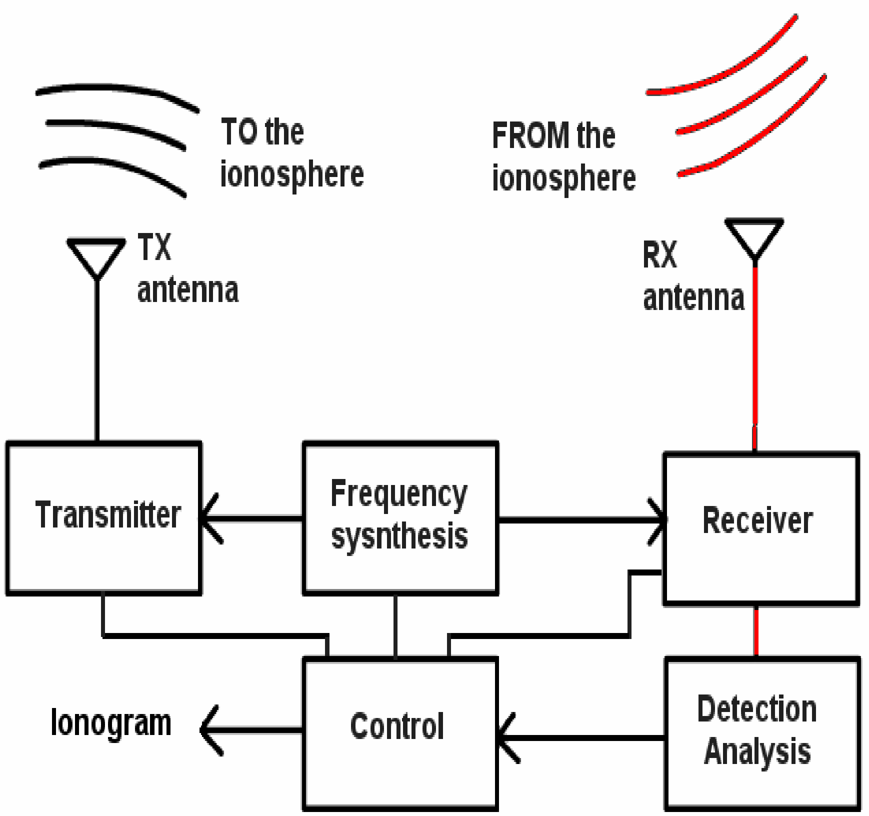
Digisonde Portal Sounder-DPS4D system

Ionosonde: Ionospheric RADAR (2/6)



- Measures ionosphere reflection height at a precise density (sounding frequency)
- Inversion process required to obtain bottom-side electron density profile
- Valleys and Topside are modeled or extrapolated

Ionosonde: Ionospheric RADAR (3/6)



Typical block diagram for ionosonde.
The way in which those functions are accomplished differentiates the ionosondes.
(Credit: Enrico and Umberto, 2010)

Basic Components:

Control system: enables the TX to emit energy; then enables the Rx to receive during the "listening time".

Frequency synthesizer: generates the frequency to transmit tuning the receiver on that frequency.

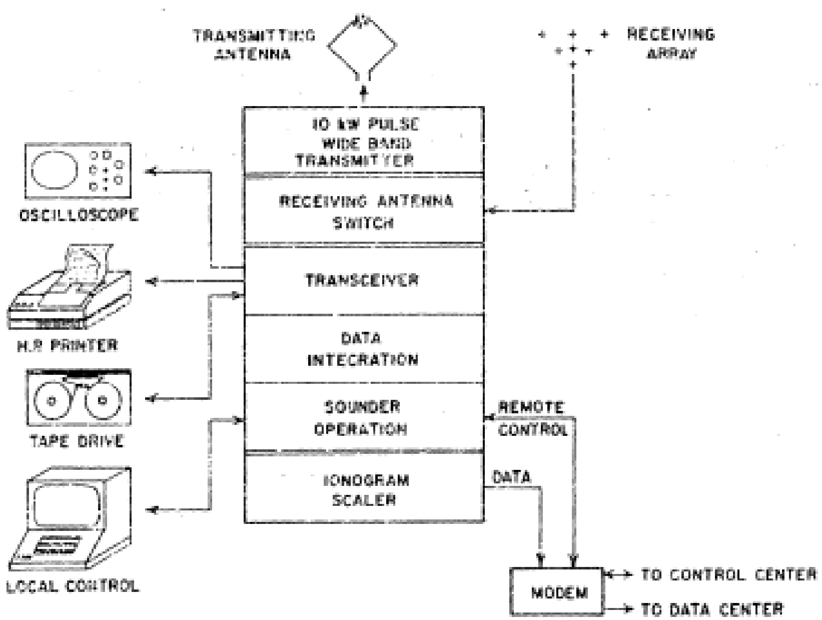
Transmitter: amplifies small signals to a proper amplitude.

Receiver: converts information at different frequencies to a more comfortable value (superheterodyne principle).

Detection and Analysis: recognizes good echoes in the noise, evaluating their delay times

Ionosonde: Ionospheric RADAR (4/6)

Variety of ionosonde designs



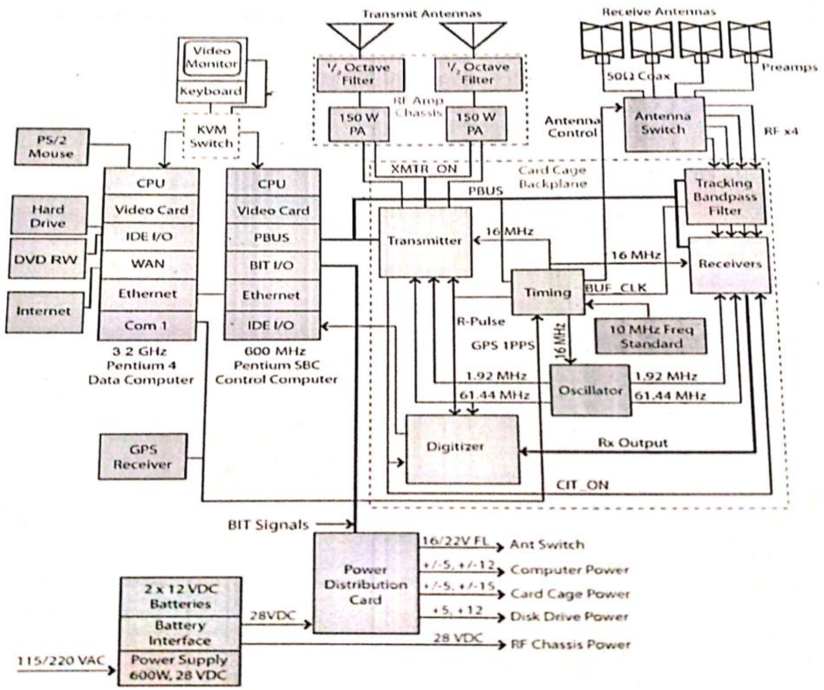


Figure 2-3 Sounder Sub-system Block Schematic Diagram

DIGISONDE 256 Block Diagram

Digisonde DPS-4

Ionosonde: Ionospheric RADAR (5/6)

Attenuation in ionosonde and their sources

Attenuation type	Source	Remark
Geometric	Signal-target path	Proportional to f and h’
Absorption	Ionized environment	High at D-region
Deviative	Top of bending trajectory	
Polarization decoupling	Rotation of polarization plane	
Focusing effects	Reflecting surface not being a perfect plane	
Ionospheric layer shielding	Masking of reflection by lower layer	e.g. blanketing sporadic E
System losses	Mismatching effects in cables	
Antennae	Frequency response	

$$P_r = \frac{\lambda^2 G_T G_r \sigma P_{rad}}{(4\pi)^3 r^4}$$

Modification of RADAR Equation is required for ionosonde as a result of the attenuation.

Ionosonde: Ionospheric RADAR (6/6)

Putting the attenuation into consideration the radar equation is modified to give the power received by the receiving antenna:

Modified RADAR equation for Ionosondes

$$P_r = \frac{(\lambda G_d)^2 P_{rad}}{(4\pi r)^2 L}$$

Where *L* represents all the attenuation

$$\frac{P_r}{P_t} = \frac{\lambda^2}{(8.\pi.h')^2} = \left(\frac{c}{8.\pi.h'.f}\right)^2$$

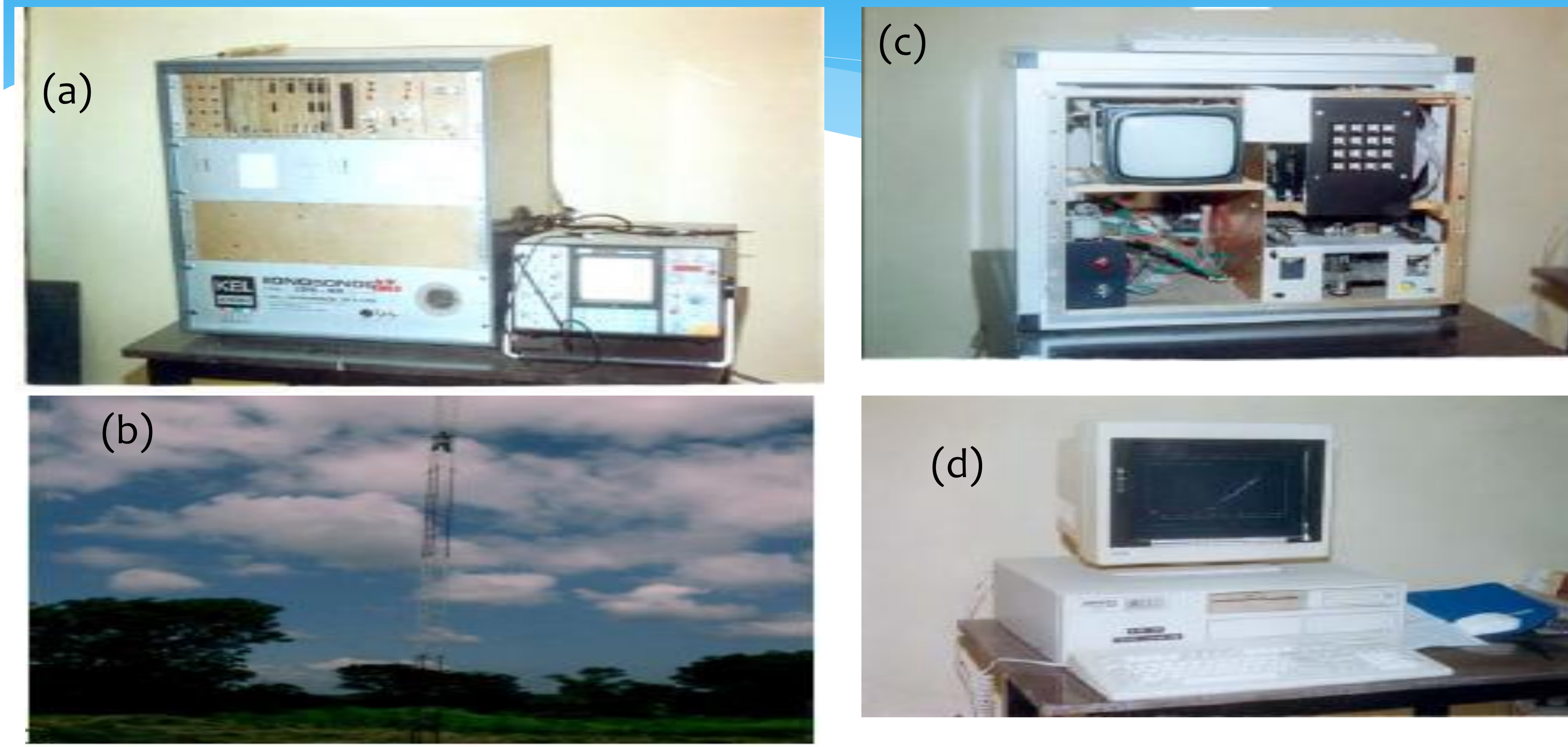
Where Pt is the power transmitted

$$Attenuation = 20.\,log\left(\frac{8.\pi.h'.f}{c}\right)\ \text{dB}$$

Types of Ionosondes

- Analog Ionosondes
- Digital Ionosondes – Digisondes
- Vertical Incidence Pulse Ionsopheric Radar (VIPIR)
- Dynasonde

Types of Ionosonde (1/3)
Analog Ionosonde (IPS-42)



(a) Transmitter-receiver and recording system, (b) Mast holding the Tx and Rx antennae, (c) Data transfer system and (d) Display and storage unit.

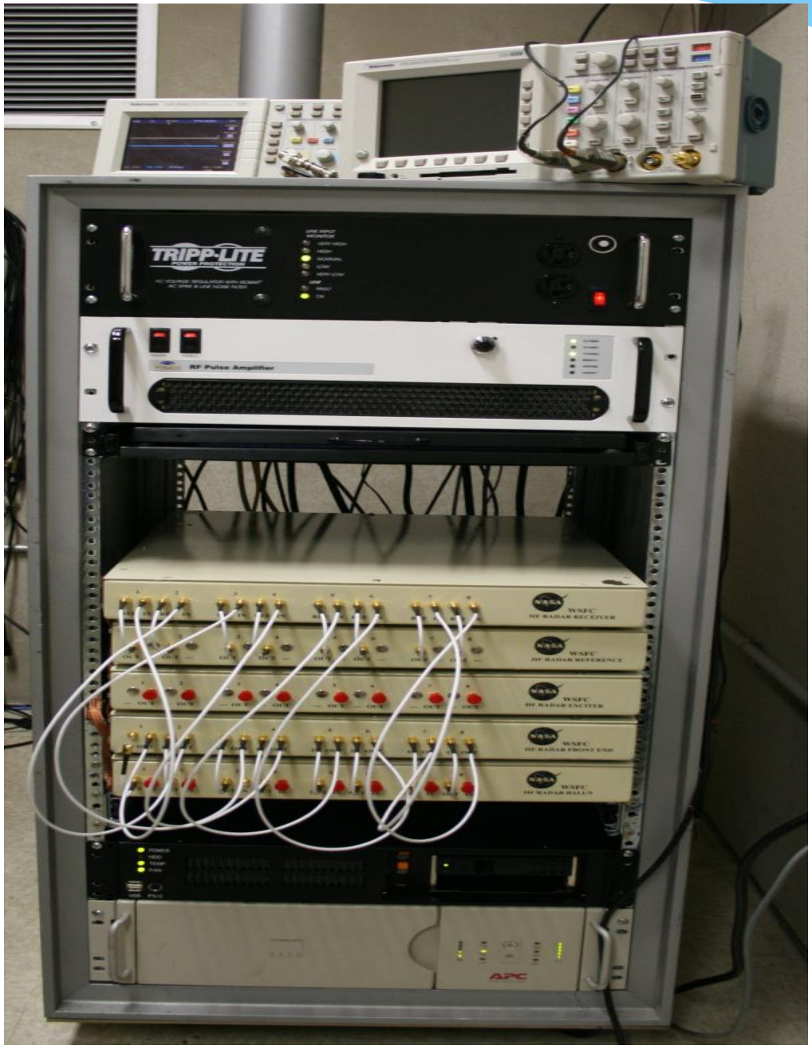
Types of Ionosondes (2/3)
Digital Ionosondes- DPS-4

Transmitting Antenna

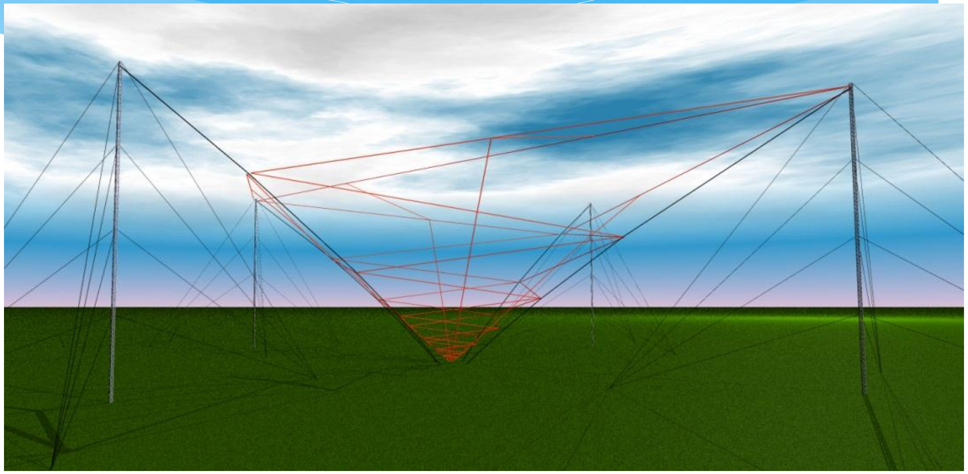
The Sounder

Receiving Antenna

Types of Ionosonde – VIPIR/Dynasonde (3/3)



VIPIR



Transmit antenna

Receive antenna

Ionosonde Technique (1/5)

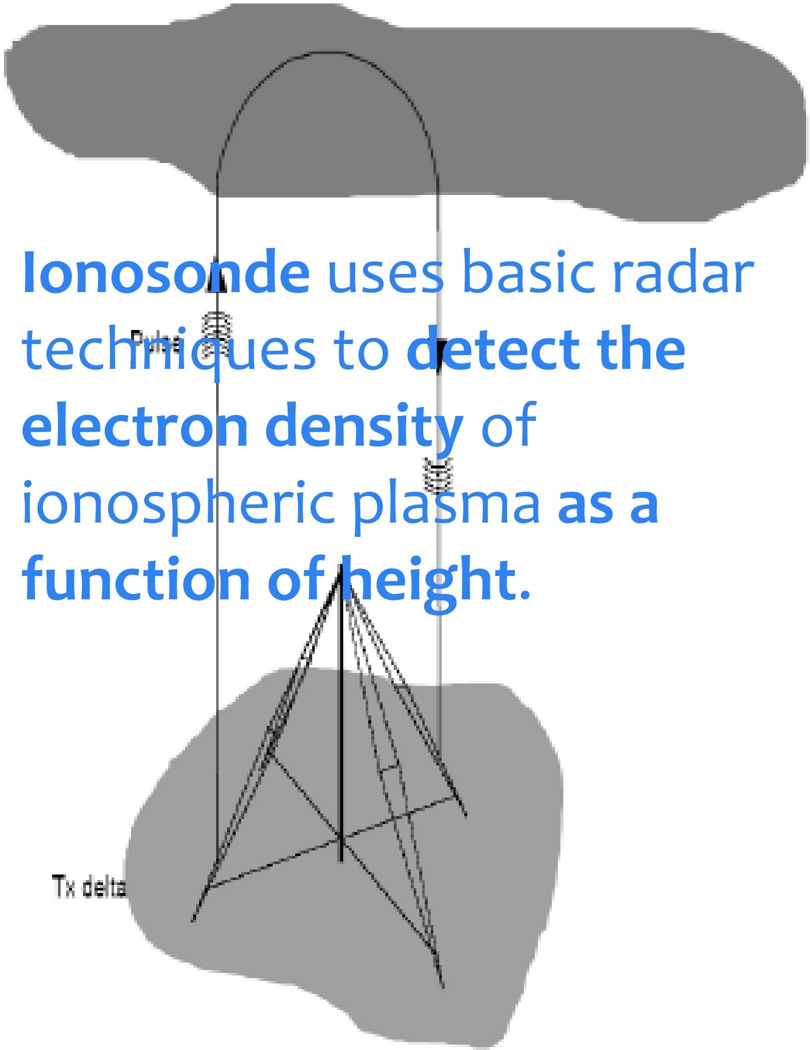
The measure technique

- **Pulses of energy at different (sweeping) frequencies are sent towards the ionosphere;**

- **The backscattered echo delay is measured to properly evaluate the position of ionospheric layers;**

- **The plasma is driven by the transmitted signal at its resonant frequency ; and**

- **Total internal reflection of the signal takes place since the relative refractive index of the ionospheric plasma is dependent on the density of the free electrons (Ne)**



Ionosonde uses basic radar techniques to **detect the electron density** of ionospheric plasma **as a function of height.**

Ionosonde Technique (2/5)

Impact of permanent magnetic field

- In the presence of permanent magnetic field, the refractive index is given by the Appleton Equation for the refractive index
- The equation gives two values for the refractive index as a result of the splitting of the wave into **O**rdinary and e**X**tra-ordinary waves.
- Since the two waves (i.e. the o- and x- waves) propagate with different wave velocities they therefore appear as two distinct echoes.
- They also exhibit two distinct polarizations, approximately right hand circular and left hand circular, which aid in distinguishing the two waves.

Ionosonde Technique (3/5)

Their critical frequencies differs;

$$f_c = 8.89\sqrt{Ne}$$

for the ordinary mode and

$$f_c = 8.89\sqrt{Ne} + 0.5\frac{Be}{m}$$

for the extraordinary mode,

where Ne is number density of electron, B is the magnetic field strength, e is electronic charge and m is the mass of electron. (Be/m) is the gyrofrequency.

Ionosonde Technique (4/5)

- **Accurate measurement of all of the parameters, depends heavily on the signal to noise ratio of the received signal.**

- **Every time the signal to noise ratio exceeds the threshold an "echo" is detected**

Probability of detection can be such that either

- **Echo is detected; Probability of detection (Pd) or**
- **There is false alarm; Probability of false alarm (Pfa)**

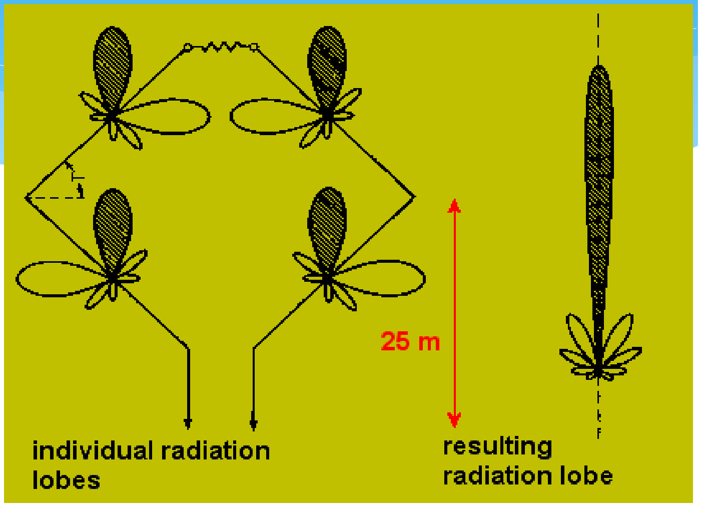
- **Both Pd and Pfa are functions of vertical transmission, signal and noise which in turn depend on the antenna.**

Antennas for vertical ionospheric sounding are therefore crucial elements in the general design.

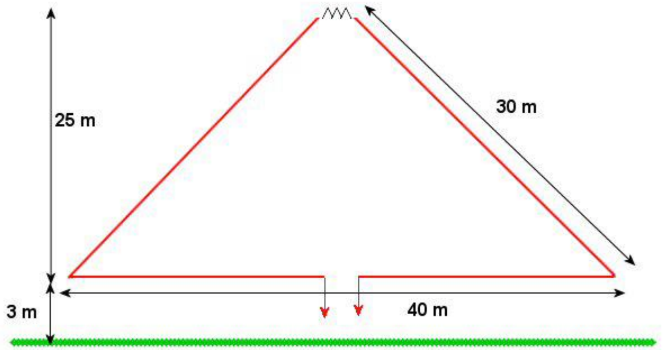
Ionosonde Technique (5/5)
Antenna Requirement

Both TX and RX antennas are design to meet certain requirements which include:

- wide band to accept the wide frequency range (a simple dipole is not allowed due to its resonance);
- the main radiation lobe needs to be directed upwards;
- they need to have a good gain because the ionospheric attenuation and the geometrical loss reduce the signal amplitude greatly.



Rhombic antenna is a simple solution that meets these requirements. A simplified version of rhombic antenna is the so called "delta" antenna

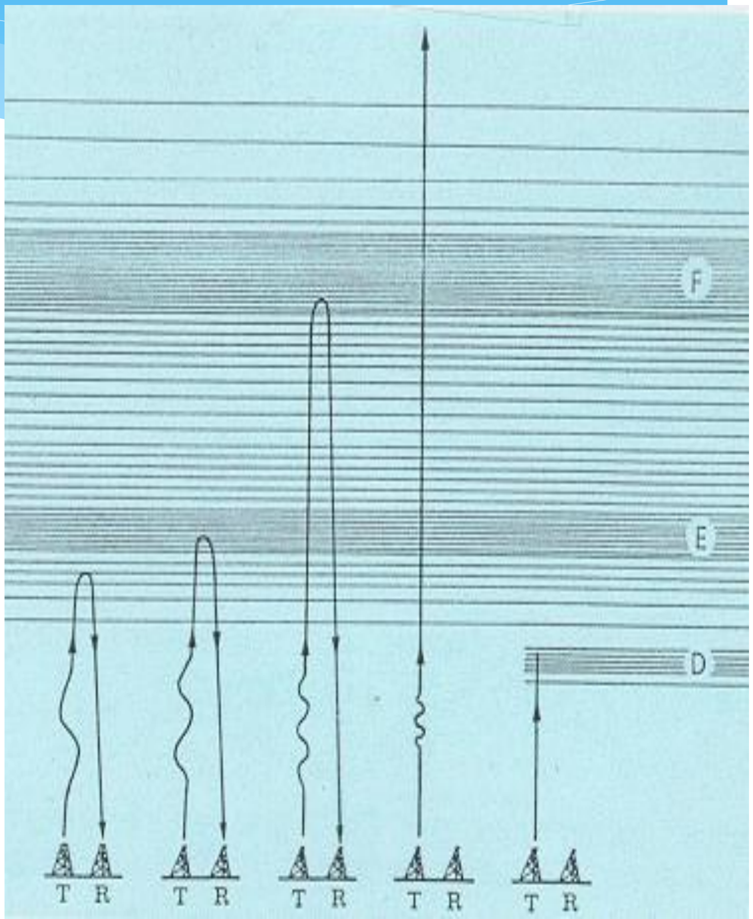


The two antennas Tx and Rx can be arranged on a single mast, 90 degrees shifted to limit cross talking.

Ionosonde: Ionospheric Sounding (1/3)

Ionospheric sounding refers to the radio detection and ranging of the ionospheric heights.

Ionosonde (chirp) transmitter generates and sends out radio signal of particular frequency through the transmitting antenna towards the ionosphere (vertical sounding).

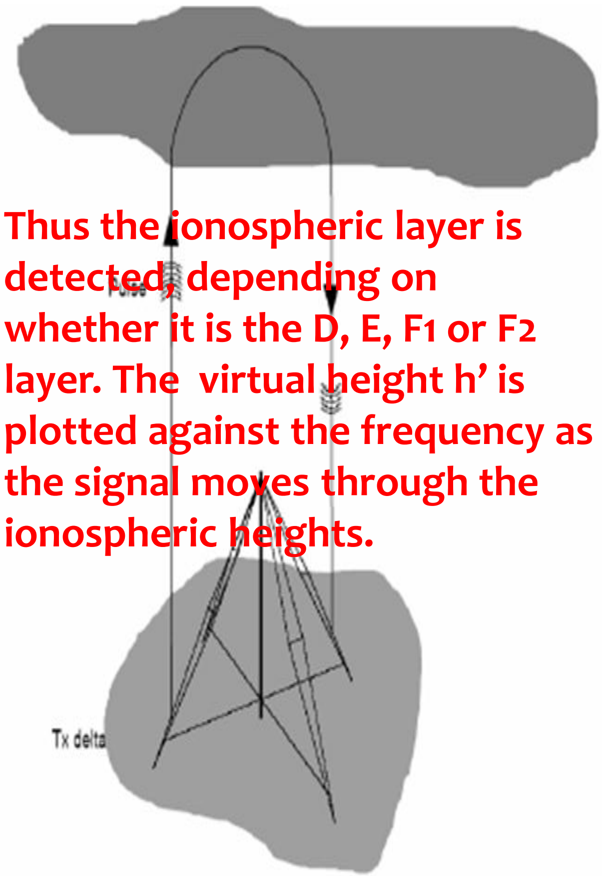


The transmitted signal reaching the ionospheric (virtual) height h' gets total internally reflected at the point within the ionospheric layer where $f = f_c$ where f is radio wave frequency and fc is the critical frequency of the layer.

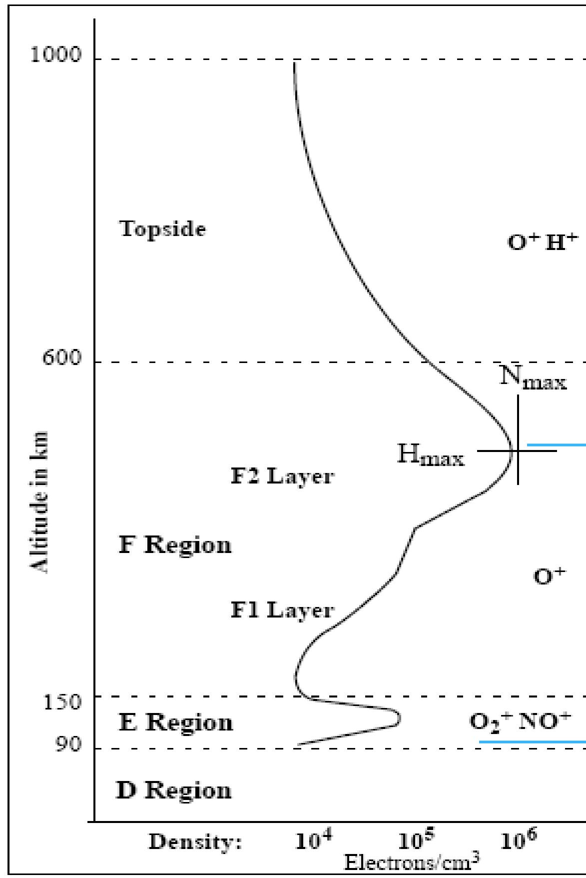
At such points the speed of the wave reduces to zero (v = 0) and the radio signal is reflected back.

The reflected signal is received by the receiver antenna and transmit to the receiver.

Ionosonde: Ionospheric Sounding (2/3)



Thus the ionospheric layer is detected, depending on whether it is the D, E, F1 or F2 layer. The virtual height h' is plotted against the frequency as the signal moves through the ionospheric heights.



By scanning the transmitted frequency from 1 MHz to as high as 40 MHz and measuring the time delay of any echoes (i.e. apparent or virtual height of the reflecting medium) a vertically transmitting sounder can provide a profile of electron density vs. height.

Maximum Ionosonde's heights of interest (bottomside ionosphere)

Ionosonde: Ionospheric Sounding (3/3)

Planning of sounding – must put into consideration:

- **Frequency limits: fmin ≥ 1.5 MHz (broad casting, anthropic noise) fmax depends on the site, the season, the solar cycle.**

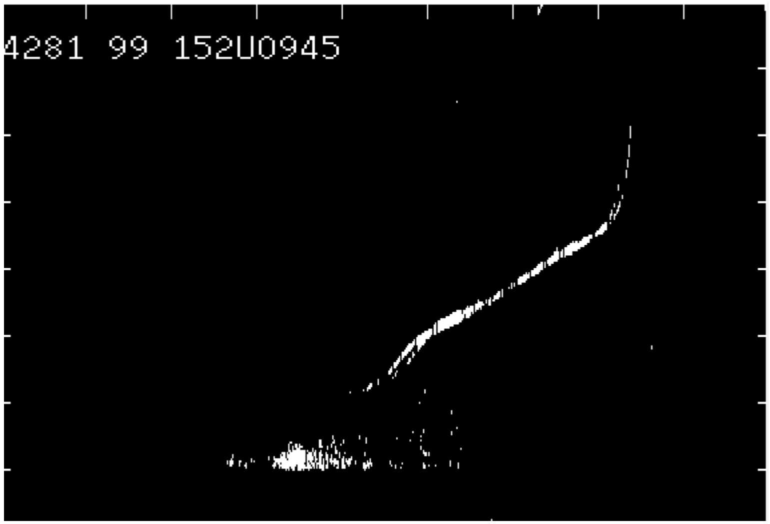
- **Frequency step: from 50 kHz to 100 kHz (rarely 25 kHz). Time integration: from fractions of seconds up to few seconds.**

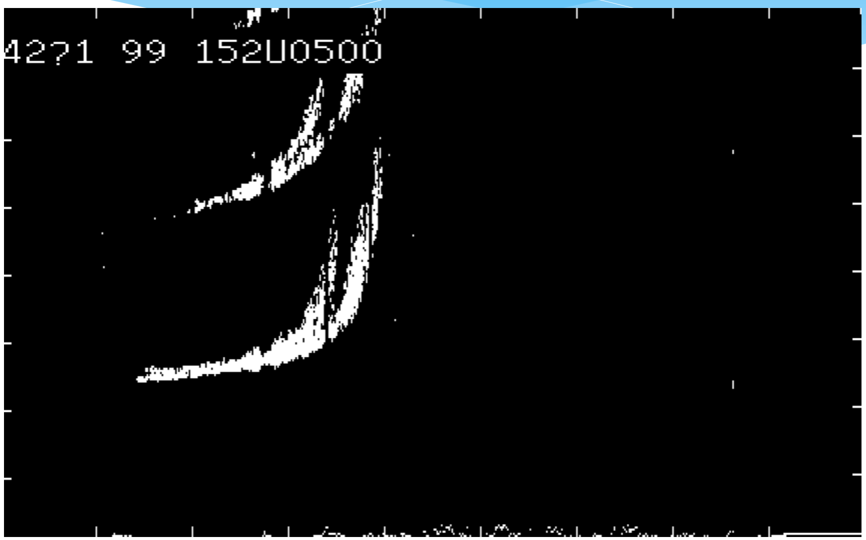
- **Sounding duration: can last from few seconds to 2 - 3 minutes .**

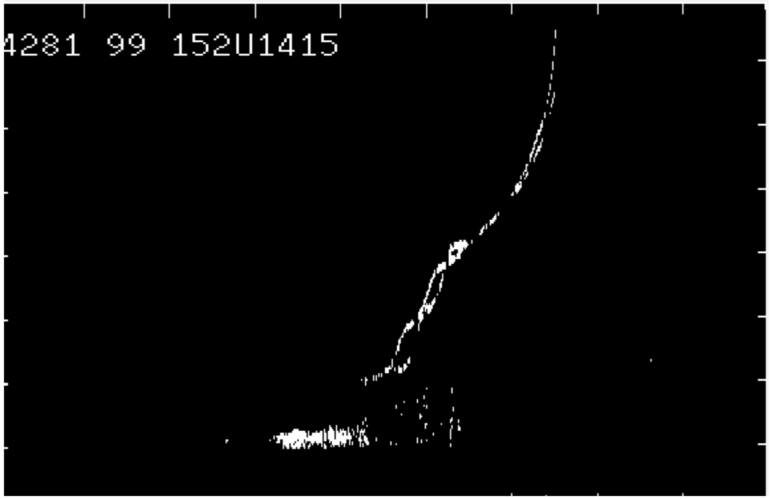
- **Soundings scheduling: depends on sounding application; routine manually scaled every hour; routine automatically scaled every 15 min; special campaign every 5 min.**

Ionograms (1/3)

sample analog ionograms

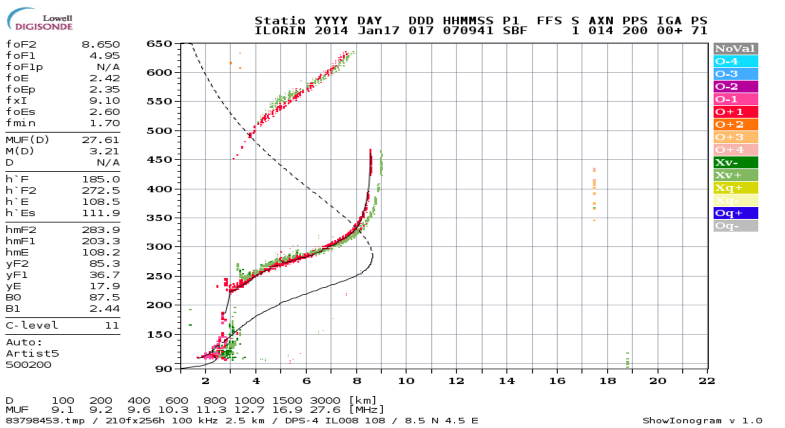


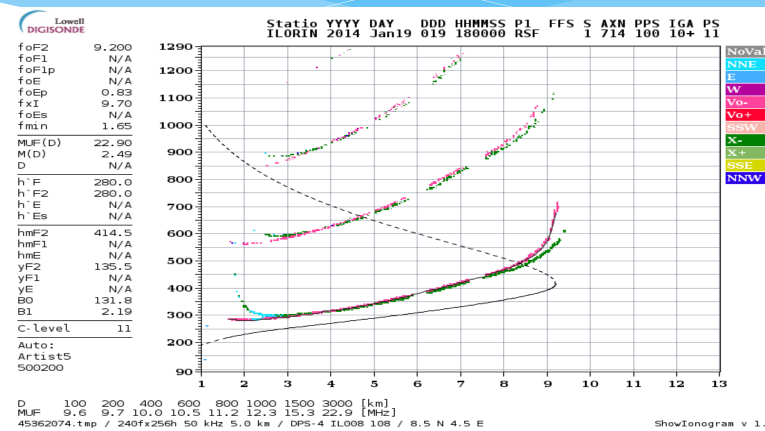


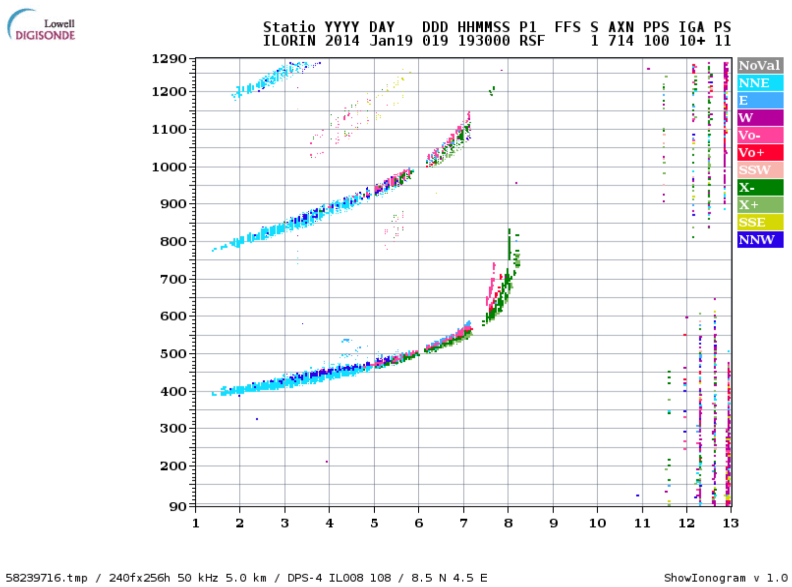


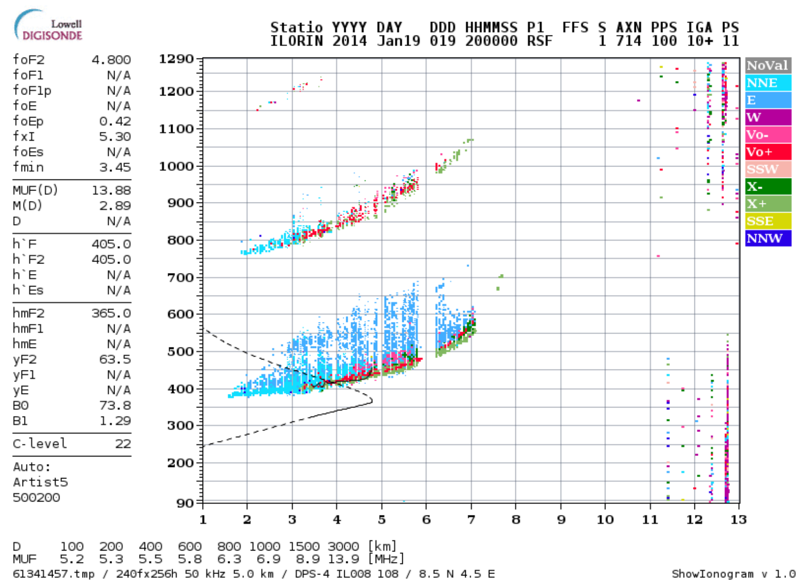
Ionograms (2/3)

sample digital ionograms

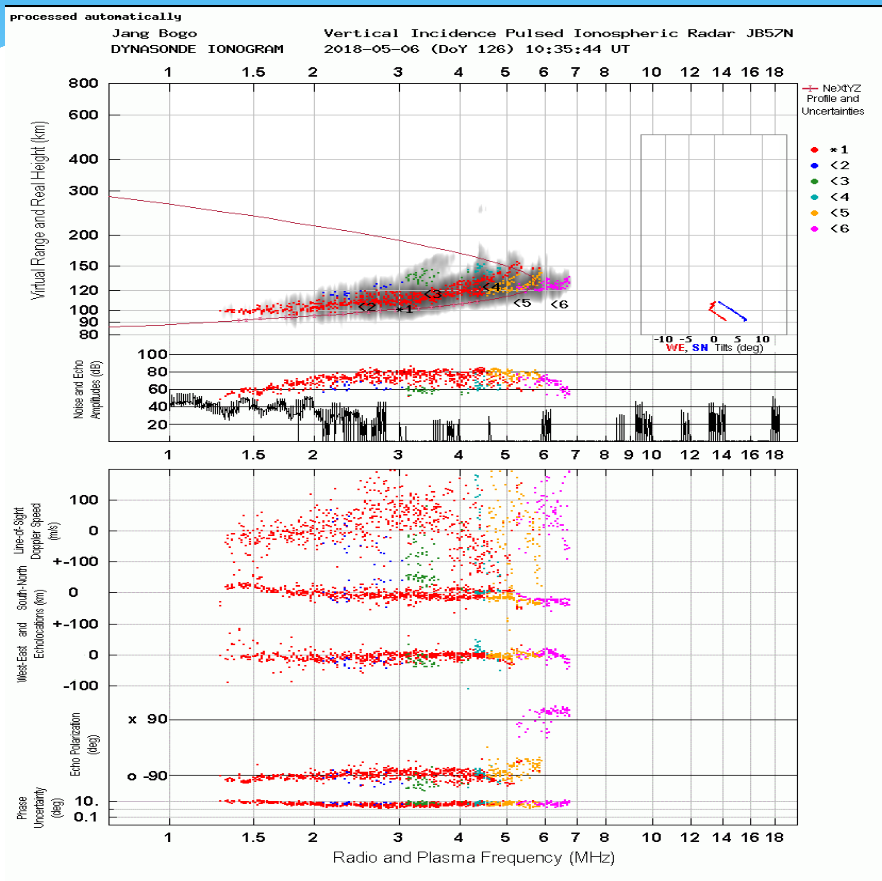




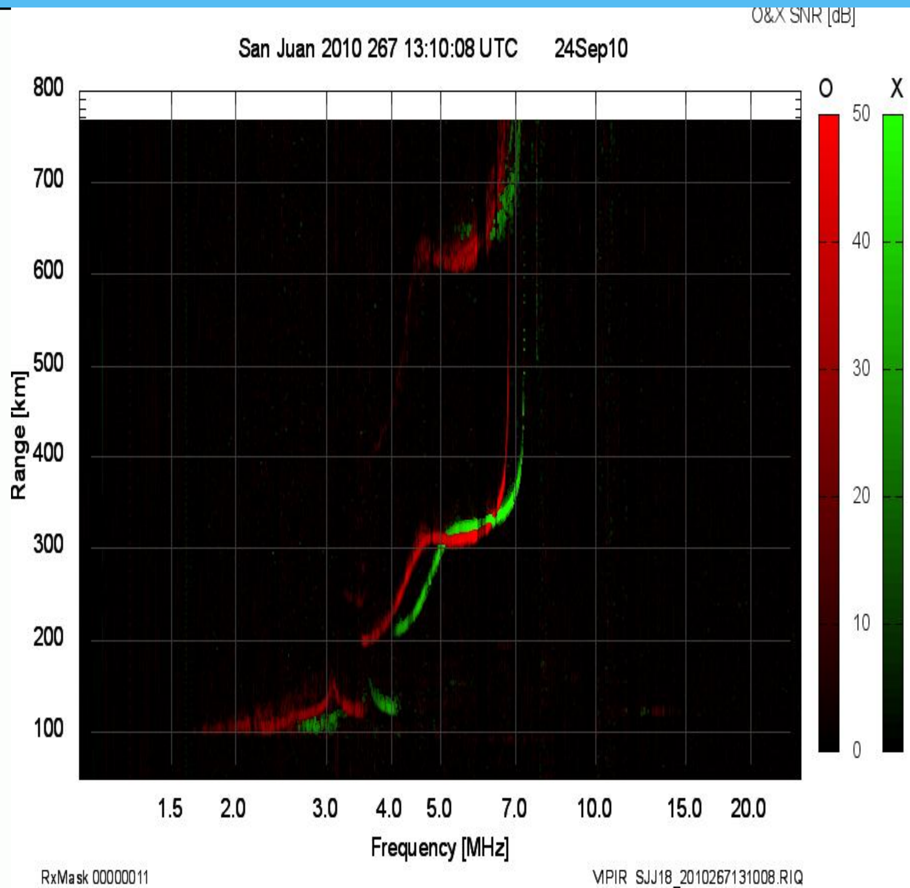




Ionograms (3/3)
sample VIPIR ionograms



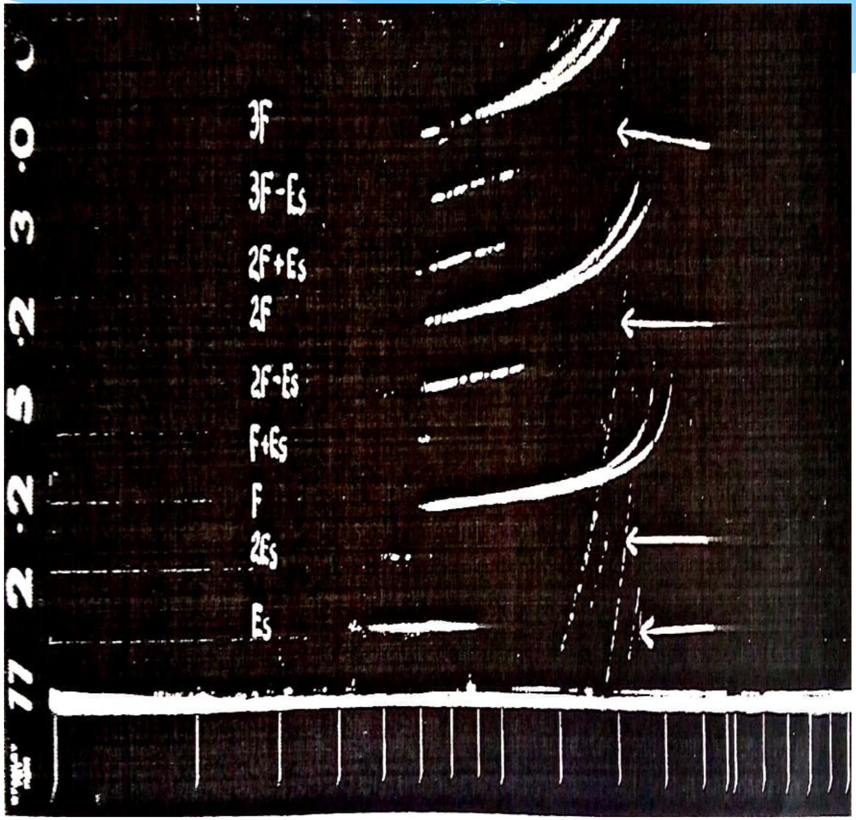
An example of the ionogram and the resulting density profile using VIPER (Kim et al., 2022)



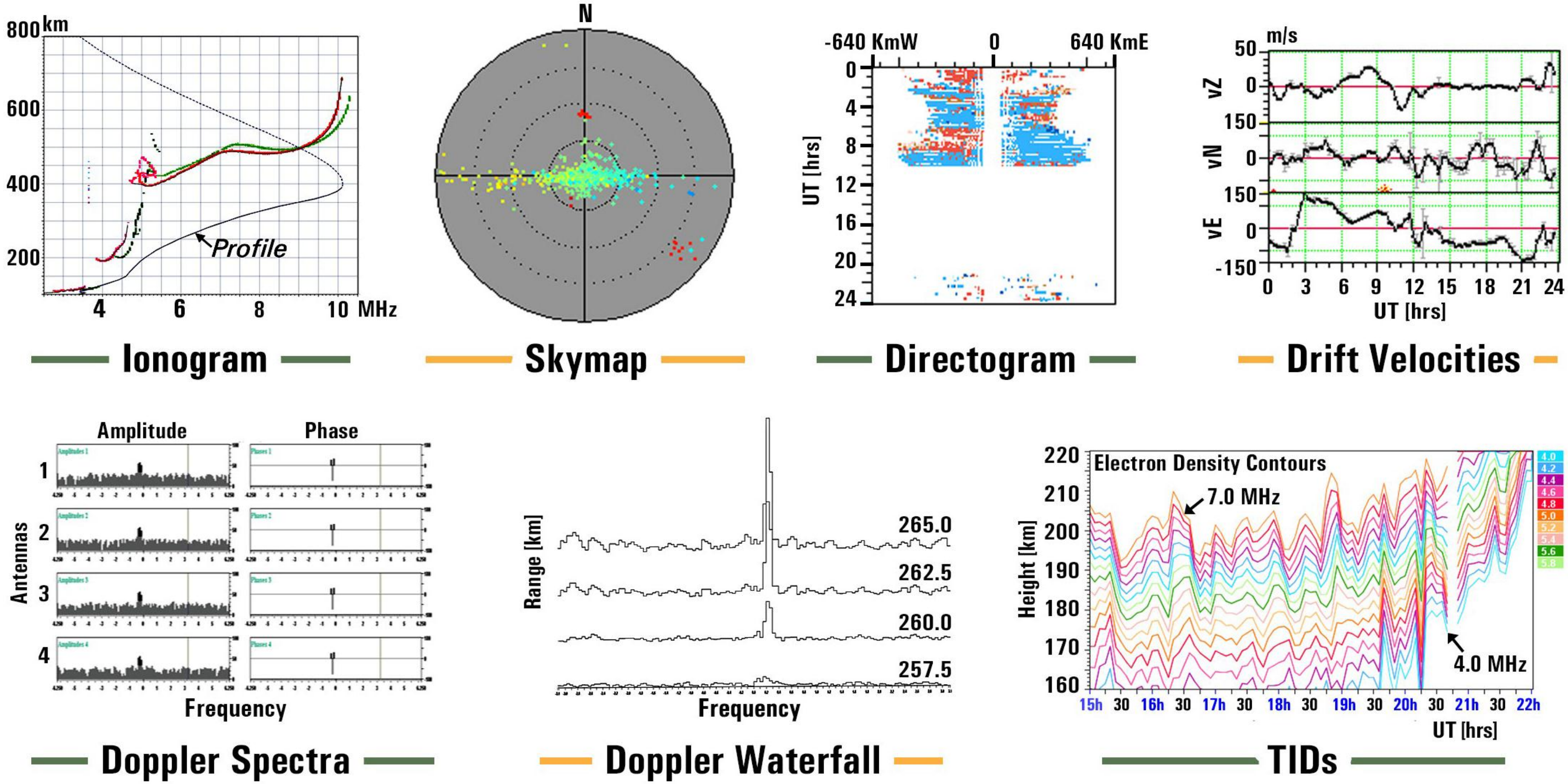
Bullet, 2011

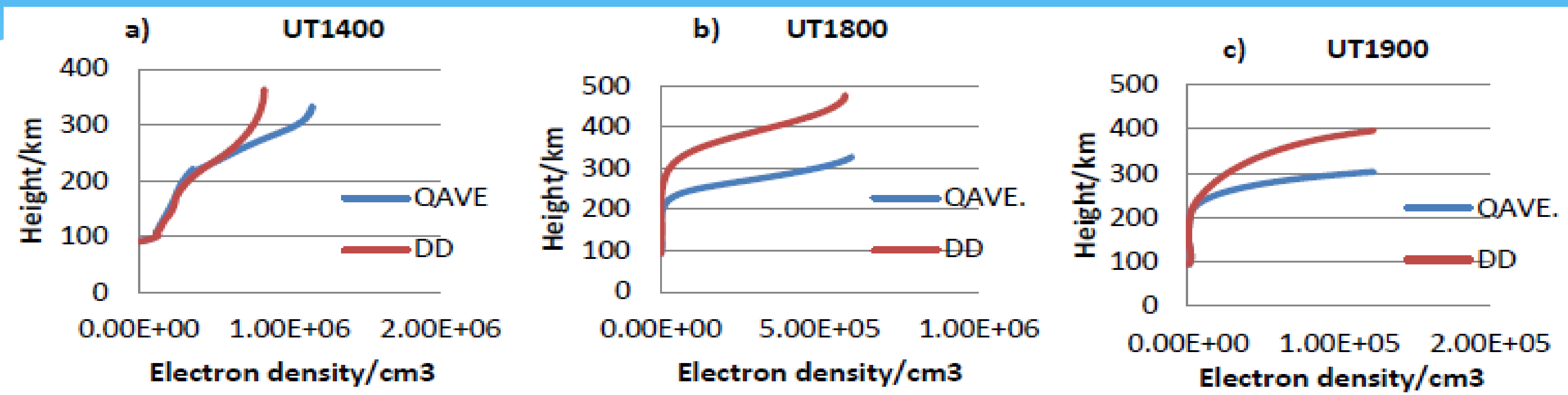
Ionograms processing

* Reduction
* Scaling
* Inversion
* Interpretation



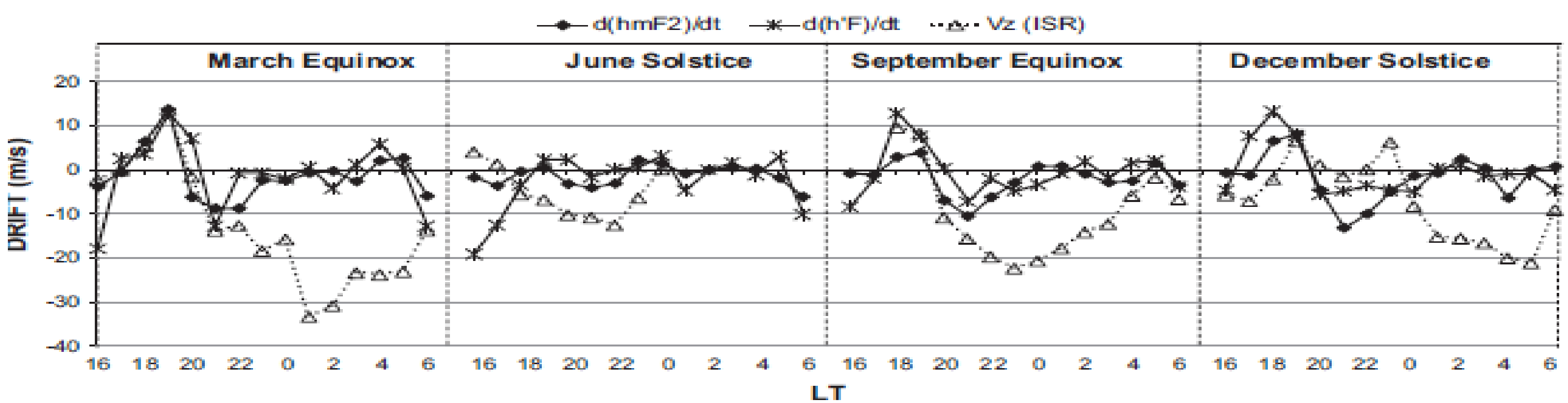
Application of Ionosonde in Ionospheric Studies





'igure 3: Effect of the main phase of storm on profile.

B.O. Adebesin et al. / Journal of Atmospheric and Solar-Terrestrial Physics 122 (2015) 97–107



$Vz_{(hmF2)}$ and $Vz_{(h'F)}$ drift inferred from digisonde measurement over Ilorin in comparison with ISR measurement over Jicamarca for March equinox, June solstice, ...ber equinox, and December solstice, 2010.

Application of Ionosonde in Ionospheric Studies

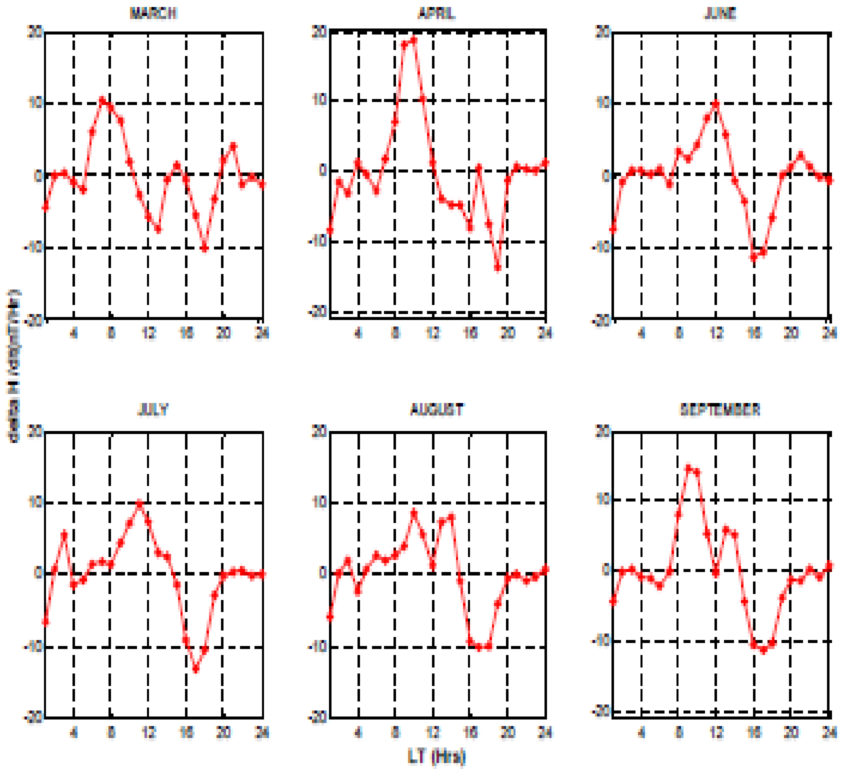


Fig. 8. Diurnal variations in $d(\Delta H_{ILR})/dt$ over Ilorin for the months of March, April, June, July, August, and September 2010. $(d\Delta H_{ILR}/dt)_{max}$ during daytime is a proxy parameter for indicating the east-west electric field in EEJ.

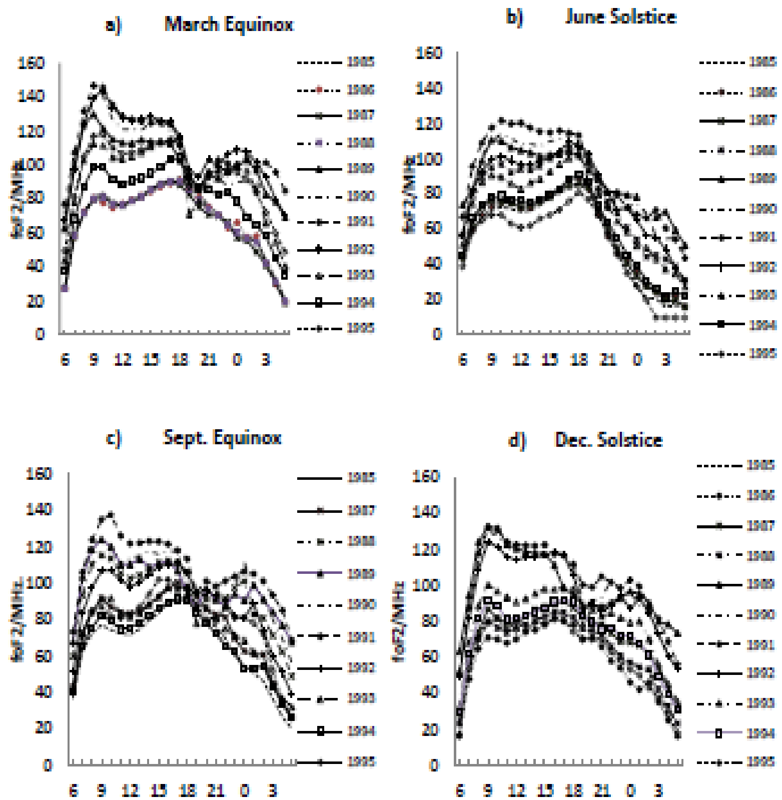
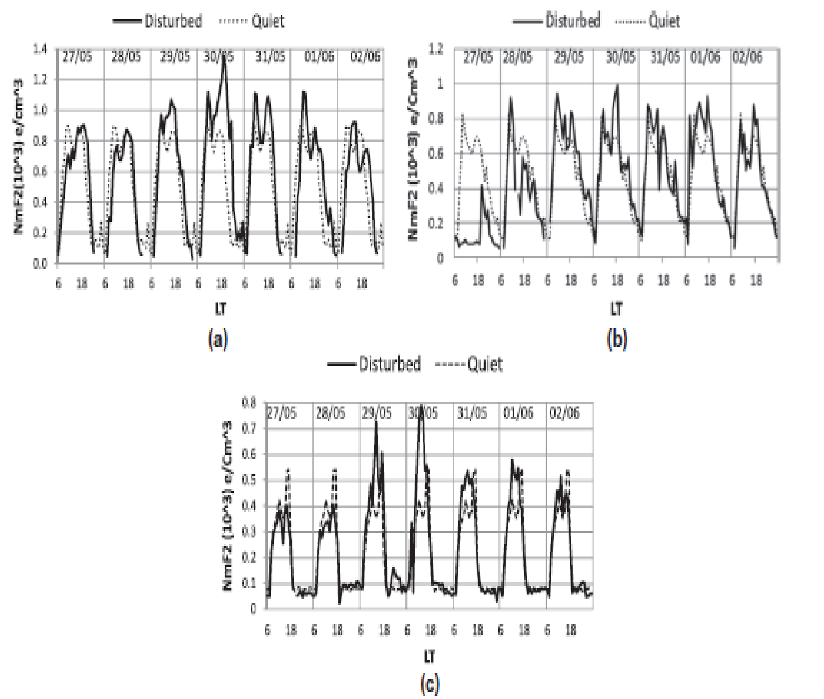


Fig.2: Seasonal variations in foF2 for all the years of the solar cycle (22) showing its solar cycle dependance.

Application of Ionosonde in Ionospheric Studies

B. W. Joshua et al. / Advances in Space Research 53 (2014) 219–225



3. Diurnal variation of NmF2 over: (3a) Ilorin, (3b) Jicamarca and (3c) Hermanus, for Average Quiet day (dark dashed line) with the disturbed d (thick dark line) during the storm of 29, 30 May, 2010. The plot spans 27 May through 2 June, 2010.

A.O. Olawepo, J.O. Adeniyi / Advances in Space Research 53 (2014) 1047–1057

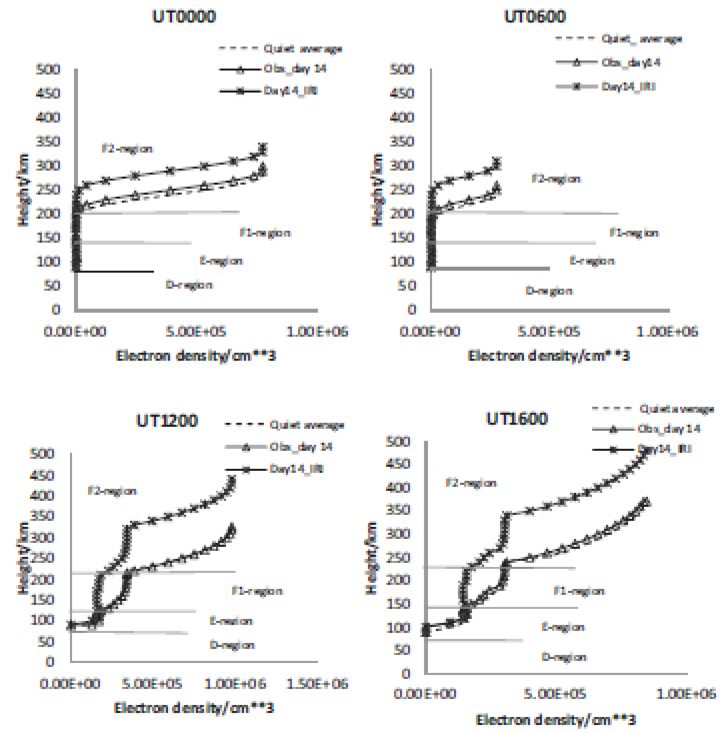


Fig. 2c. Plots comparing IRI-07 storm model prediction with observed storm time profile during 14 Jan., 1999.

Application of Ionosonde in Ionospheric Studies

Olawepo *et al.* ILORIN JOURNAL OF SCIENC

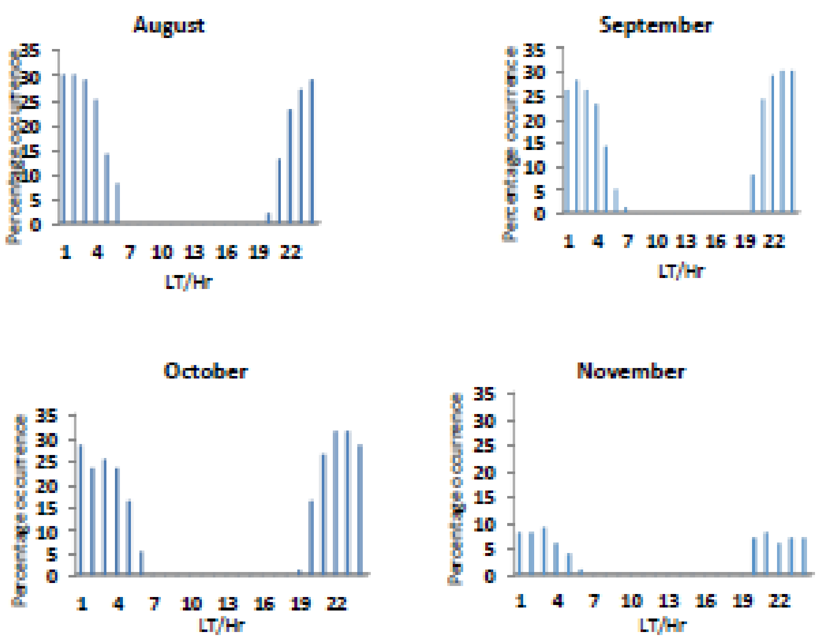


Fig. 2: Diurnal percentage occurrence of spread F over the months (Data for January and December were available.

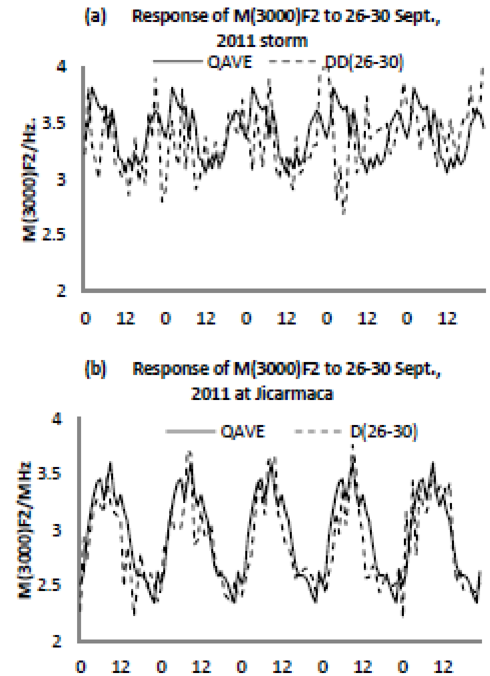
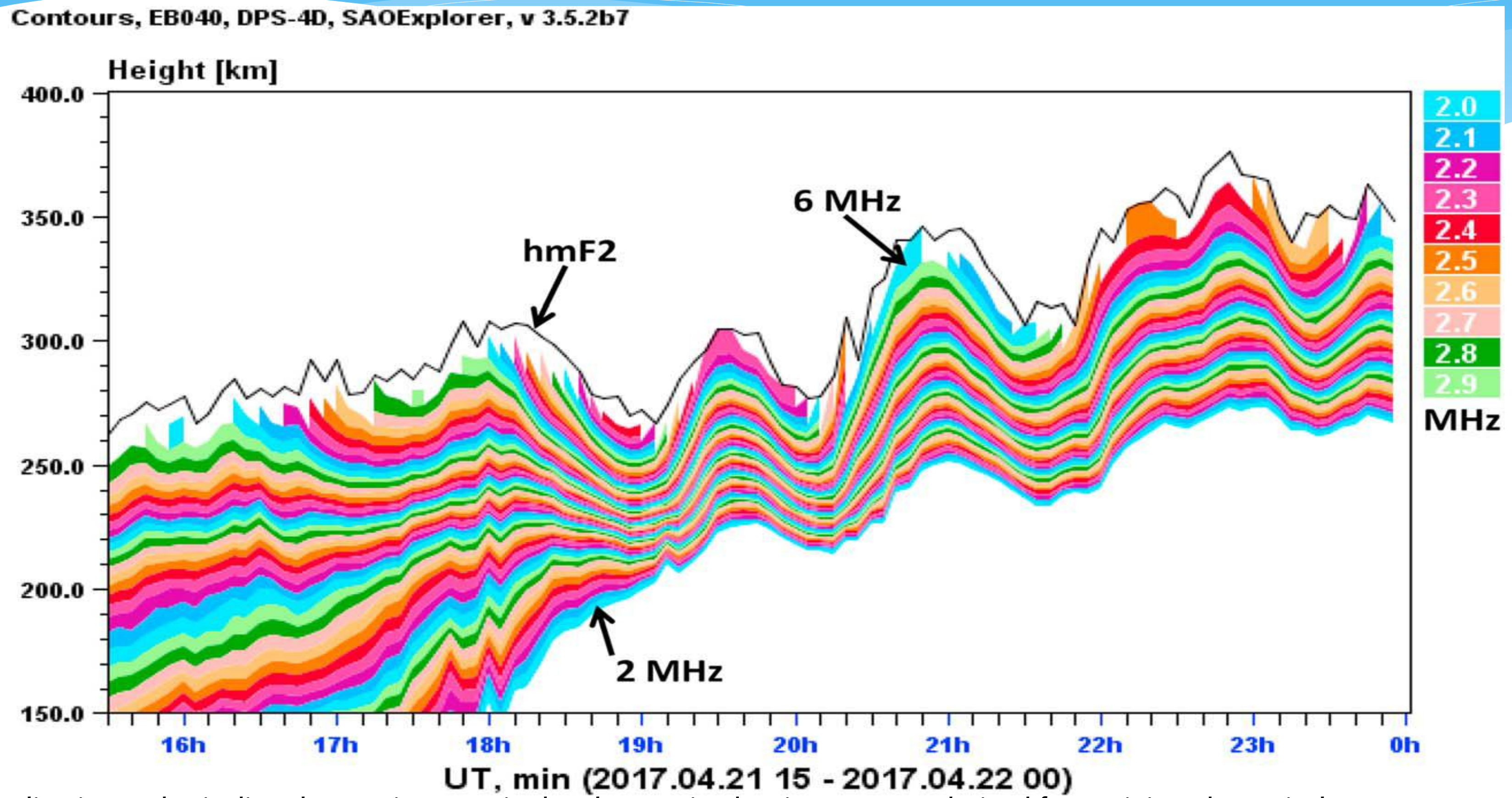


Fig.9: M(3000)F2 response to the events of 26-30 Sept., 2011 at (a) Ascension Island and (b) Jicarmaca

Application of Ionosonde in Ionospheric Studies



Traveling ionospheric disturbance signature in the electron isodensity contours derived from Digisonde vertical ionogram meaurements at the Ebro Observatory (Roquetes, Spain).(einich et al, 2018)

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Thanks for your attention

Q & A