Propagation of Radio Signals in presence of the Ionospheric D-Layer: an essential element when planning Radio Communications Network

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***Abstract*—Loss of radio signals in the ionospheric D layer in presence of the Sun, including the day-night transition hour are the challenging problems when planning a radio communications network and predicting propagation of radio signal. An overview of the electron density of the different layers of the ionosphere and the mechanism of radio waves propagation have highlighted first. Our study suggests that the noise powers in the days of perturbed meteorological condition is smaller than those in the days associated with the solar bursts. A comparison of the received signal during daytime in presence of the Sun and after sunset is done for different occasions in the ELF/VLF bands which show that there is a clear indication of signal attenuation during daytime.**

Keywords*—radio signals; ionosphere; radio communications; radio wave propagation; solar burst

I. Introduction

Propagation of radio signal through the ionosphere is an important and fascinating means for long distance radio communication. Commercial operators in different parts of the globe use the ionosphere for transmitting signal over long distances. In order to make the propagation effective we need to know the interfering factors in the propagation path of the transmitted signal. Radio signals in the form of electromagnetic waves when travel from transmitters to receivers, they interact with objects and the media through which they move. During this journey the radio signals can be reflected, refracted or diffracted causing change of direction of the radio signals. The ionosphere has a major role and may be considered as one of the key areas when planning a radio communications network or at a preliminary level when investigating signal propagation conditions. For any successful communication, in addition to the behavior of the ionosphere the troposphere plays a crucial role over the transmitted signal which propagates crossing the meteorological layer of the troposphere where lightning has a major contribution in the form of atmospheric noise affecting the propagated signal.

II. Backgrounds

The first step in using electromagnetic waves in space for radio communication was taken by James Clark Maxwell when he came up with "the theory of the electromagnetic field" in 1873. Maxwell considered that magnetic waves undergo to reflection, refraction, and absorption like light wave [1]. The existence of these waves was first demonstrated by Heinrich Rudolph Hertz in some experiments carried out in 1888 [2]. This study based on the basis of Guglielmo Marconi experiments with wireless telegraphy using Morse code. In 1896, Marconi was successful in sending signals through a wireless telegraph to a distance of a few kilometers away [3]. The problem then came was to consider the possibility to provide intercontinental communication by radiotelegraphy and radiotelephone. In 1901, together with his assistants, G.S. Kemp and P.W. Paget, Marconi successfully transmitted and received transatlantic signals between Poldhu, Cornwall and New Foundland, Canada, using a kite aerial at Signal Hill in Cornwall, England [4-6]. Since that time, radio and radiotelephone communications largely started its journey for human benefits. After a short time, human beings were able to arrive at a stage that helped them to conduct transatlantic communications using radiotelegraphy. Sky waves are the AM radio waves, which are received after being reflected from the ionosphere. The radio wave signals from point to point propagation via reflection from ionosphere are recognized as sky wave propagation. The sky wave propagation is an important consequence of the total internal reflection of radio waves. As the depth of ionosphere increases the free electron density also increases [7]. Consequently there is a decrease of refractive index. Thus, as a radio wave travels up in the ionosphere, it finds itself traveling from denser to rarer medium. The signal continuously bends away from its path till it faces total internal reflection to come back at the Earth [8].

Even before Sir Edward Appleton's pioneering work in 1925, it had been suspected that ionization of the upper parts of the Earth's atmosphere played a part in tile propagation of radio waves, particularly at high frequencies [9]. It is shown from the experimental work of Appleton that the atmosphere gains sufficient solar energy that helps its molecules to ionize. Thus, they remain ionized for long periods of time [6, 9]. He also showed that there were several layers of ion at various heights so the high-frequency waves reflected back to Earth otherwise they would have escaped into space. The various layers of the ionosphere have specific effects on the propagation of radio waves [10]. The frequency spectrum of electromagnetic waves ranges from the "sub-sound frequency region" (1Hz) to cosmic rays. Radio communication is made using the electromagnetic waves that form part of this frequency spectrum. Similarity or differentiability of the radio waves is determined by the frequency band that determines their wave length. Radio waves move at the speed of light (300 thousand km per second), much faster than sound itself, so to find the wave length of a radio wave, we divide its velocity by its frequency. Frequencies used within the radio frequency spectrum measure between 20 KHz and 30 GHz [11]. Scientists have divided the atmosphere into seven layers in order to reveal the unknown facts about it. These seven layers are different from each other in terms of temperature, pressure and humidity levels, and the natural events that occur in them. If we ascend from the Earth toward the sky, we pass through the layers of the troposphere, stratosphere, ozonosphere, mesosphere, thermosphere, ionosphere and the exosphere. Each of the atmospheric layers serves a vital cause. Every layer has many functions, ranging from the formation of rain clouds to the prevention of harmful beams reaching the Earth, from reflecting radio waves to inactivating meteors [12].

III. Ionosphere and the Importance of Radio Waves in Modern Communication

The solar UV radiation in the ionosphere is so intense that when it strikes the gas molecules they ionize causing an electron set free to affect the radio waves [13]. Electrons number start to increase at altitude of nearly 30 km, though the electron density is not enough to affect radio waves until at a height of about 60 km. Ionosphere has got some distinct layers, referred to as D, E and F. The height of different ionospheric layers during daytime in presence of the D layer and during night in absence of the D layer is presented in Figure 1.

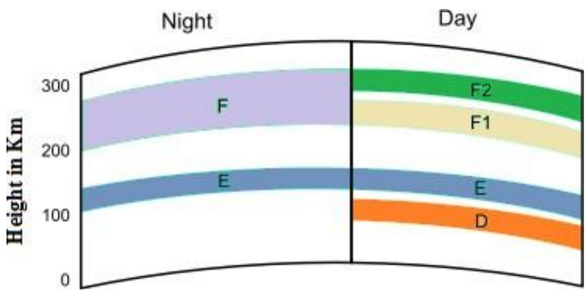

Fig.1 Height of different ionospheric layers during daytime in presence of the D layer and nighttime when it disappears

The figure shows that the D layer is the lowest layer of the ionosphere at altitudes between 60 and 90 km which appears during daytime when radiation is beaming in from the Sun. When the solar radiation is blocked after sunset, the electron levels rapidly reduce and the D layer disappears. The next ionization level above the D layer is known as the E layer whose altitude lies between 100 and 125 km and the altitude of the layer is maintained both during day and night. Because electrons and ions recombine relatively quickly here, ionization levels drop quickly after sunset. Although a small amount of residual ionization persists, the E layer virtually disappears at night.

Radio waves are e. m. waves with wavelength 10^{-3} m or more, having frequency from kHz to MHz range [14]. Propagation of radio waves is applied in all modern communication like radio, television, microwaves etc. Radio signal when reaches at the D layer, it behalves like an attenuator, particularly at low frequencies which varies as the inverse square of the frequency. This indicates why low-frequency signals are obstructed for going to the higher layers, except at nighttime when the D layer is no longer present. Signals when pass through the D layer are attenuated since they can produce free electrons to vibrate [15, 16]. When this happens, the electrons collide with other molecules and thus consuming a small amount of energy and dissipating a proportionately small amount of radio signal. Radio communication depends on many factors, like frequency of the radio waves, season of the year, position of the Sun, location of the broadcasting area and time of day. Depending on the frequencies and ionization, radio waves are partly absorbed in the ionosphere and partly refracted to the outer space or are reflected to the earth again [17]. The variation of electron density with height of the ionosphere is presented in Figure 2 in addition to temperature vs. height.

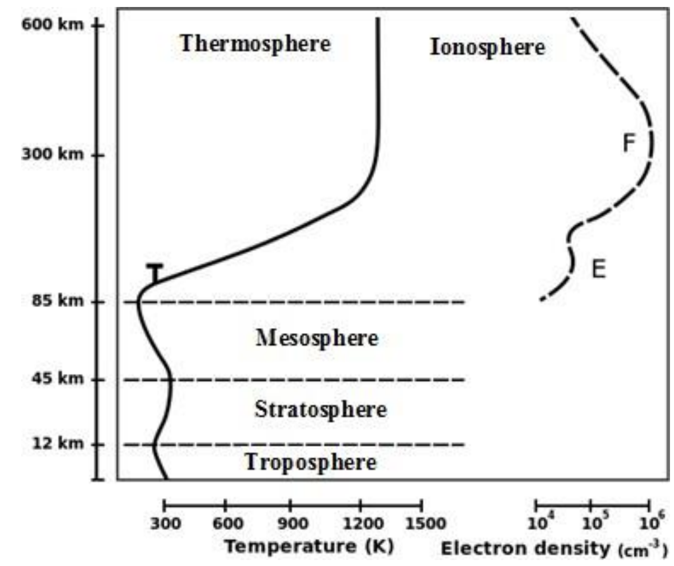

Fig.2 Relationship of thermosphere and ionosphere showing the variation of temperature and electron density with height

The level of attenuation depends on the number of collisions take place, in addition to a number of other factors [18]. With the increase of frequency, wavelength becomes shorter and collisions between free electrons and gas molecules reduce. Consequently, low-frequency signals are attenuated far more than those at high frequencies. When the signals enter the E layer they cause free electrons to vibrate. Here the air density being much lower, collisions are less and hence less amount of energy is lost [19]. The electrons thus tend to re-radiate the signal.

IV. Lightning as Electromagnetic Radiation

Electromagnetic radiation radiated during terrestrial lightning discharges may be received by a sensitive receiver which is known as sferics. The sferics so produce are superposed over the radio signal transmitted at different frequency bands from transmitting stations. Similar to lightning discharges, other terrestrial phenomena like strong thunderstorm and cyclonic activities and similar disturbances while entering the Earth's atmosphere produce e. m. radiations due to their interaction with the medium, which propagate and reach the surface of the Earth. We have used Sferics Receiver, Log-periodic Dipole Array (LPDA), Spectrum Analyzer and Digital Storage Oscilloscope for capturing the radio signals originating from lightning discharges in the ELF, VLF and LF bands as well as solar bursts in the VHF and HF band. In order to calculate the power of each signal pattern we have used the relation,

$$Power\ Power_{dB_m} = (Av.\ point\ 1023) - 1\}XF\ \dots . (1)$$

In equation (1) the Average point data is referred to as 10 bits DAC value obtained from the spectrum analyzer by converting the SPF file to .txt file which contains the date and time of when making the SPF file, center frequency, resolution bandwidth (RBW), reference level, span and 501 points of data. Since it is the record of measurement, therefore more than one measured data could be stored; F is the center frequency of the recorded signal in Hz and R is the reference level in dBm adjusted in spectrum analyzer.

Noise signals recorded at overcast cloudy condition before the occurrence of lightning at 10 kHz and two other harmonically related frequencies, viz., 20 kHz and 30 kHz are shown in Figure 3.

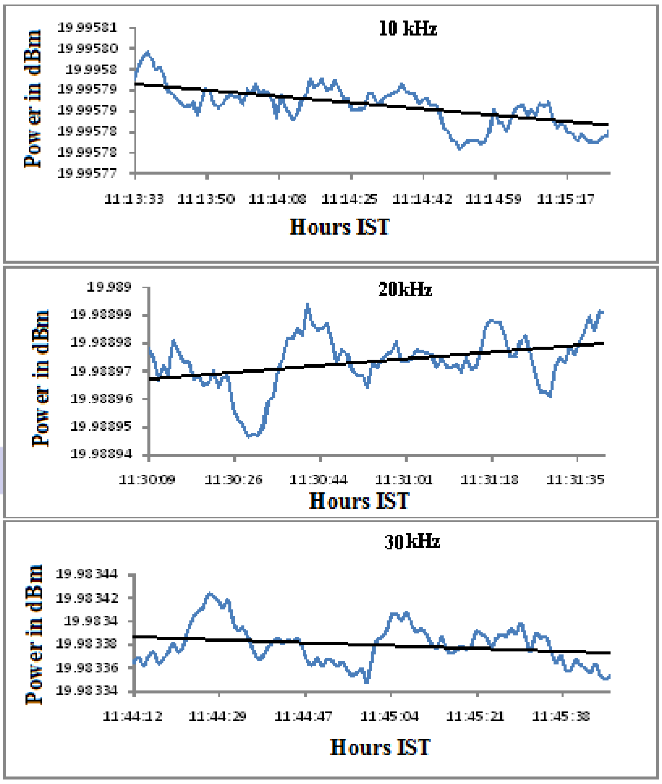

Fig. 3 Sferics records at 10, 20 and 30 kHz at overcast cloudy condition on March 4, 2015

Figure 4 exhibits a typical sferics record at 10 kHz when lightning discharges occur at the observing site.

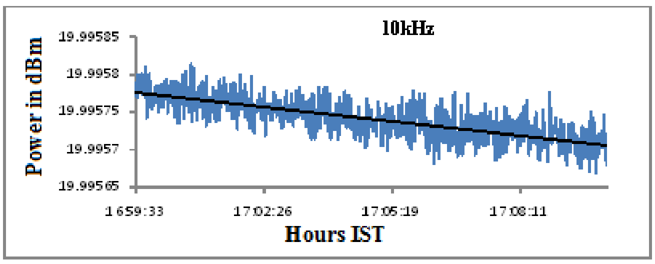

Fig. 4 Sferics at 10 kHz during lightning discharges at the observing site on March 30, 2015

V. SOLAR BURST DATA AS RECORDED BY LPDA

The Sun‟s apparent surface, the photosphere, radiates more actively when there are occurrences of greater number of sunspots. Sunspots are usually formed in the active regions of the Sun. An active region on the Sun is an area with especially strong magnetic field and appears bright in X-ray and ultraviolet images. Solar activity, in the form of solar flares and coronal mass ejections (CMEs), is frequently associated with active regions. Solar burst signals recorded on different dates in February by LPDA are shown in Figure 5 while some other records when occurrences of greater number of sunspots were reported in some occasions of March, 2015 are presented in Figure 6.

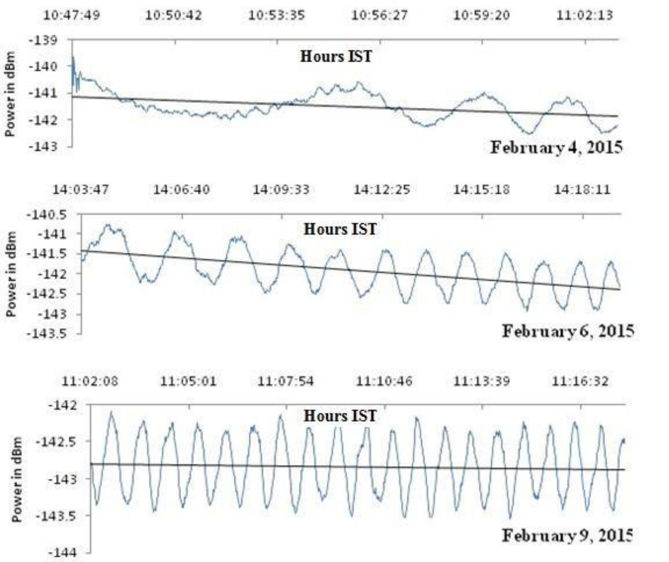

Fig. 5 Solar Burst signal recorded at 170 MHz at different dates on February, 2015

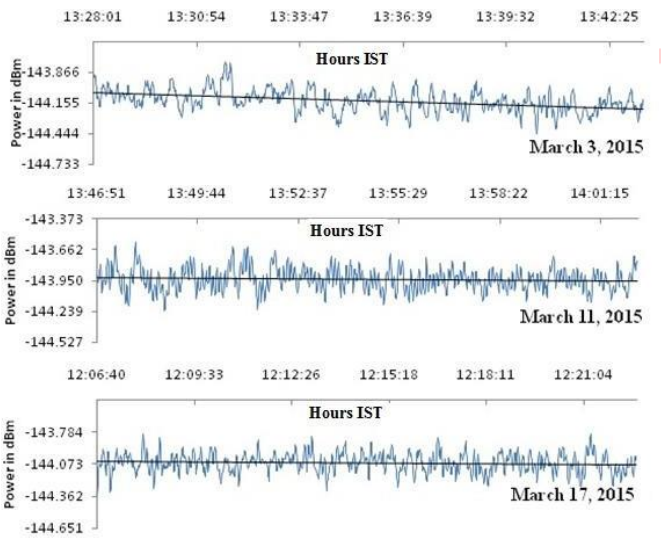

Fig. 6 Some other solar burst signal recorded at 170 MHz in March, 2015

Analyzing the data for a period of one year it has been observed that the noise power in the days of perturbed meteorological condition is smaller than the noise power in the days associated with the solar bursts. Again it has been noted that the noise power is larger in the days associated with the solar bursts compared to the sunny days without burst.

VI. ELF AND VLF RADIO SIGNALS RECORDED AT TIU

It is well known that when the propagation occurs over a good conductor like seawater, particularly at frequencies below 100 kHz, surface absorption becomes small. Also, the attenuation owing to the atmosphere at such times becomes low. The angle of tilt then becomes the main determining factor in the long distance propagation of such waves. Conversely, due to the large wavelengths of VLF signals, waves in this range are able to travel long distances before disappearing. At distance up to 1000 km, the ground wave is remarkably steady, showing little diurnal, seasonal or annual variation. The effects of the contribution of E- layer to propagation at long distances are especially important during day-night transition at sunset hours. Typical radio signal recorded at Techno India University using the „Spectrum lab software‟ (RAS make) is shown in Figure 7(a) where left hand panel of the spectrum analyzer shows ELF pattern centered at 1.3780 kHz frequency. The ELF radio signal, shown on the left, reveals that the ELF pattern takes the value of about -75 dB; which then attenuates gradually at the VLF end to a value -110 dB. The peak value of the ELF signal as shown from the record is nearly -5 dB.

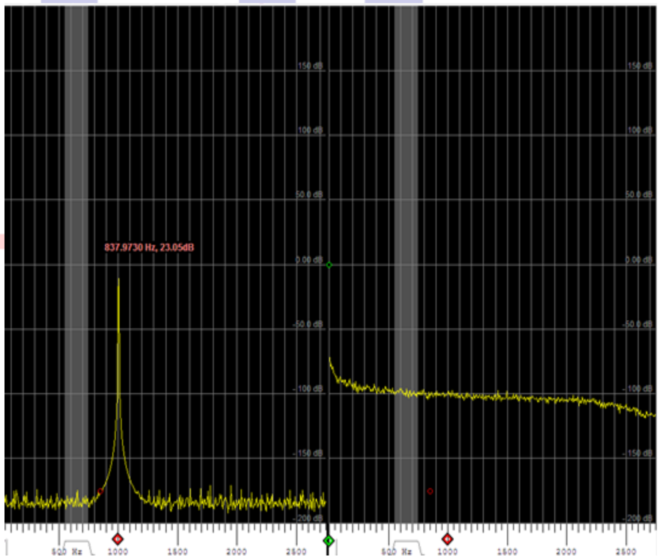

Fig. 7(a) Typical radio signal data in the ELF and VLF bands

Another radio signal data has presented in Figure 7(b) for the purpose of showing the VLF records more prominently on a clear day in the frequency range from 3 kHz to 14 kHz.

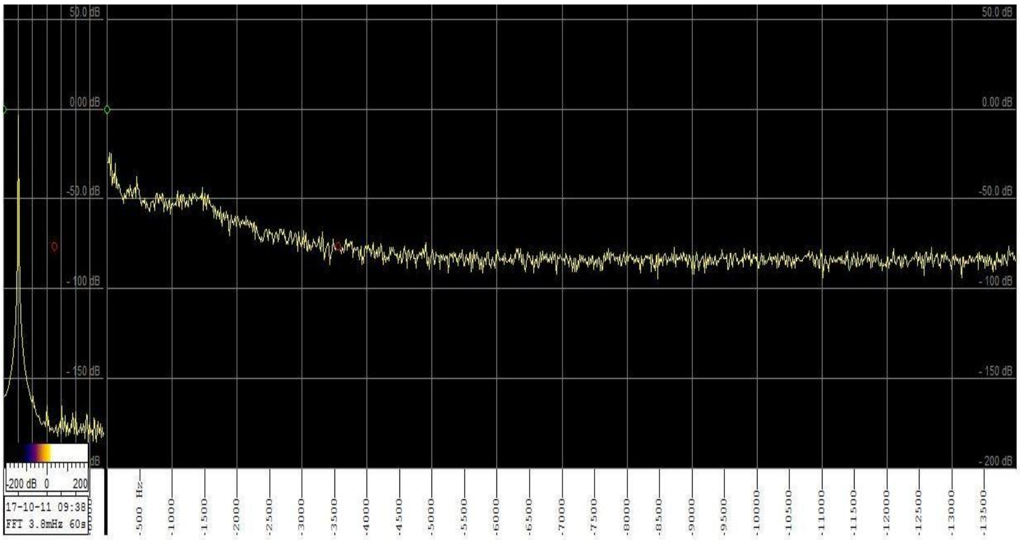

Fig. 7(b) Spectral pattern of the Radio signal data in the VLF band on a clear day in the frequency 3 kHz to 14 kHz

A comparison of the received signal during daytime in presence of the Sun and after sunset is done for different occasions which show that there is a clear indication of signal attenuation during daytime. A simple estimation of the same is illustrated in Figure 8.

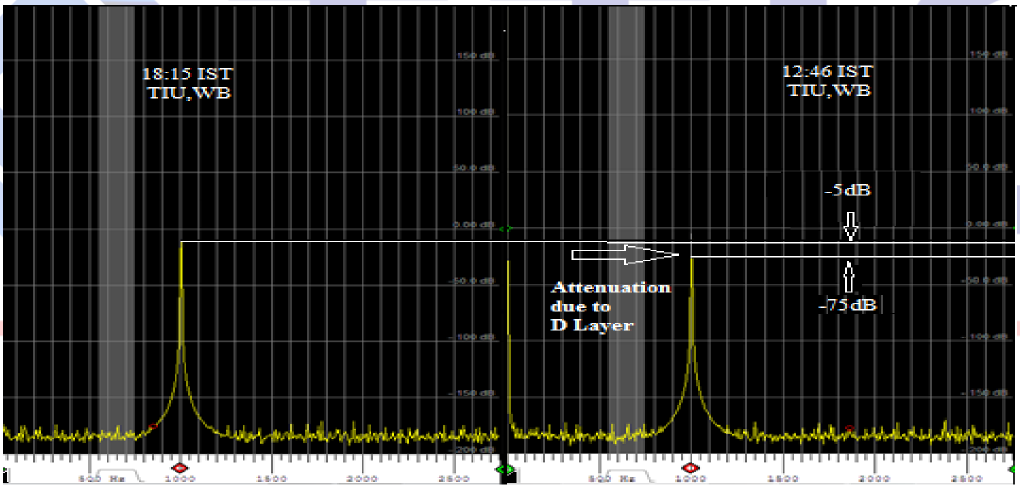

Fig.8 Comparison of the radio signal data during daytime in presence of D layer and during night when D-layer disappears in the ELF band

VII. Discussions

During daytime the medium-wave signals are reflected and pass back through the D layer in course of their propagation and return to Earth at a considerable distance from the transmitter. Apart from losses suffered due to reflections at the Earth‟s surface, signals are attenuated each time when they pass through the D layer of the ionosphere. In fact, D-layer attenuation is particularly important when we consider that the signals have to reflect from the D layer by multi-hop propagation [20]. Ionization of the D layer is caused by Lyman series-alpha hydrogen radiation at a wavelength of 121.6 nm, ionizing nitric oxide (NO). Moreover high solar activity can produce hard X-rays of wavelength < 1 nm, that ionize N_2 and O_2.

Radio waves at different frequency bands are significantly attenuated within the D layer, since the passing radio waves move electrons which collide with the neutral molecules, giving up their energy. Lower frequencies get higher absorption because they move the electrons farther, leading to high chance of collisions [21]. The ionosphere is assumed as an area where the radio waves on the short wave bands are either refracted or reflected back to Earth. Radio signals are reduced in strength when they pass through this area and hence ionospheric absorption can be taken as the major contributors for the reduction in signals strength [22].

Proper selection of frequency for radio communication is an important factor for successful propagation of any signal. It may be noted that for transatlantic communications conducted through communication satellites, radio waves of more than 30 MHz are used in practice [16]. If the artificial satellites are within the limited coverage area, they imitate the ionospheric layer and work as a reflector for these waves (Figure 9).

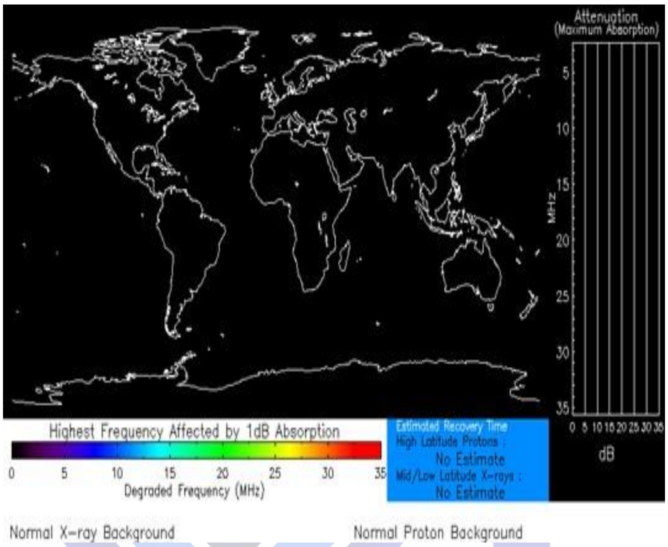

Fig. 9 Attenuation of radio signals at MHz frequencies [23]

It is important to mention that for radio waves less than 30 MHz, the ionosphere serves as a natural satellite. Because of this characteristic of the ionosphere, we do not have to give special emphasis on any particular parameter, rather to consider all the responsible parameters simultaneously at a certain point. For searching new facts about the universe and other related problems like the effects of lightning or solar bursts, we need to know more clearly the propagation mechanism of the radio signal during transient variations with adequate data.

Acknowledgments

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References

[1] http://www.fountainmagazine.com/Issue/detail/The-Importance-of-Ionosphere-in-Radio-Communication

[2] Camalan, M., **"**The Importance of Ionosphere in Radio Communication, Science**"**, *The Fountain Magazine***"**, Issue 55**,** 2006**.**

[3] https://www.scribd.com/document/265968296/ionosphere-and-telecommunicationb.c.

Blevis, "The pursuit of equality: the role of the ionosphere and satellite communications in canadian development", *Ionosphere and Telecommunication*,1974

[4] Harding, S,R., Register of the George H. Clark Radioana Collection c. 1880-1950, by Archives Center, National Museum of American History, Washington, DC, 1990.

[5] Bondyopadhyay, P.B. , "Investigations on the Correct Wavelength of Transmission of Marconi's December 1901 Transatlantic Wireless Signal", *IEEE Antennas and Propagation Society*, International Symposium Digest, Vol. **1**, pp. 72 -75,1993.

[6] Reception of Transatlantic Radio signals, 1901 Signal Hill, Newfoundland Dedicated October 1985 - IEEE Newfoundland-Labrador Section

[7] Bilitza., Dieter., "International Reference Ionosphere 2000" *Radio Science.* **36** (2): 261–275,2001

[8] Bhattacharya, A, B., Das, T., "Tropospheric Ionospheric Coupling by Electrical Processes of the Atmosphere", *International Journal of Application or Innovation in Engineering & Management(IJAIEM),* **2**, Issue 5, 2013

[9] Brittain, E, J., "Electrical Engineering Hall of Fame: Edward V. Appleton [Scanning Our Past]", *Proceedings of the IEEE* ,**98**, Issue: 9, 681 – 1682, 2010.

[10] Effect of Ionosphere on Radio Wave Propagation, *International Journal of Research* Daniel,A., Tilahun, G., Teshager, A., **03** Issue 09, 2016.

[11] Whitney, H,E., Aarons,J., Malik, C, "A Proposed Index for measuring Ionospheric Scintillation", *Planetary and Space Science*, United States Air Force, Environmental Research Paper,No-284,1969 - Elsevier

[12] Bhattacharya A. B., Pandit, J., Bhoumick, A., Halder, A., Sarkar, A., Raha, B., Bhattacharya, R.,"Orionid Meteor Shower and its effect on Ionospheric Propagation", *International Journal of Theoretical and Applied Physics* ,**2**, pp. 219-229,2012.

[13] Mahmoudian, A., Scales, W.A., Bernhardt, P, A., Fu,H., Briczinski, S.J.," Investigation of ionospheric stimulated Brillouin scatter generated at pump frequencies near electron gyroharmonics", *Radio Science journal* , **48**, Issue 6, ,Pages 685–697,2013

[14] http://k9la.us/The_Structure_of_the_Ionosphere.pdf

[15] Nertney, R. J., "The lower E and D region of the ionosphere as deduced from long radio wave measurements", *Journal of Atmospheric and Terrestrial Physics*, **3**, Issue 2, p. 92-107. 1953.

[16] Rana, G., Yadav. M,K., "The ionosphere and radio propagation" *International Journal of Electronics and Communication Engineering & Technology*, **5**, Issue 11, 2014, pp. 09-16

[17] Dicati, R., "Stamping the Earth from Space", *Springer*, 2017,pp-60-124

[18] http://www.qsl.net/zl1bpu/IONO/iono101.htm

[19] http://www.radio-electronics.com/info/propagation/common/atmosphere.php

[20] https://www.arrl.org/files/file/Technology/pdf/119962.pdf

[21] Moldwin, M., "An Introduction to Space Weather", *Science*, Cambridge University Press, pp 86-88, 2008.

[22] https://en.wikibooks.org/wiki/Communication_Systems/Wave_Propagation

[23] http://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap