Detection and analysis of aperiodic ionospheric D-layer disturbances

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***Abstract*— This paper provides overview of a procedure developed for detection and analysis of non-periodic ionospheric D-layer disturbances induced by solar X-ray flares, intensive γ-ray bursts, cyclones, earthquakes, etc. This procedure is universally applicable for primary VLF and LF signal processing, which we use for spatial radio probing of the lower layers of ionosphere.**

I. Introduction

From the aspect of the telecommunication Earth atmosphere represents complex medium and introduces number of the adverse factors impacting on telecommunications signals. Within Earth Atmosphere, there is a number of the ongoing processes as well as intermittent events which as a consequence, among other things, affect the propagation of electromagnetic waves. Earth Atmosphere is generally decomposed in five layers: troposphere (lowest atmospheric layer, averaging 12 km from the Earth's surface, thinner at the poles, and thicker at the equator), stratosphere (from around 12 km to up to 50 km from the Earth's surface, ozone layer is located here and temperature averages 0 Celsius)**,** mesosphere (which is located above the stratosphere, from 50 km to 80 km above Earth surface inside this layer atmosphere is tin and cold, around -90 Celsius), thermosphere (starts above stratosphere, from 80km to 700 km above Earth surface, this layer is characterized with high temperature, reaching 1000's degrees Celsius, and energetic movement of gases), exosphere (most outer layer, starts above the thermosphere, from 700 km up to 10 000 km). The air and gases within Earth's Atmosphere are ionized by the Sun's radiation. This ionisation creates ionosphere. Ionosphere overlaps the multiple atmospheric layers. Ionosphere is continuously changing, for example there are difference between ionosphere during day time (spreading through mesosphere, thermosphere, and parts of the exosphere), and night time (mainly affecting thermosphere and lower exosphere). Ionosphere is also affected by variations in solar activity and Earth's climate. In general Ionosphere is divided in to three layers: the D, E (Heaviside-Ennelly), and F (Appleton). These ionized layers affect the propagation of telecommunication waves. Ionosphere as a part of the Earth's atmosphere, in particular affects the propagation of ULF (300 Hz – 3kHz) ,VLF range (3-30kHz) and LF range (30-300kHz) [1]. By observing the emission of real and known electromagnetic signal in ULF, VLF or LF range on the receiving end we can analyze processes which take place in the lowest layer of the ionosphere by varying the parameters of the known signal. In order to detect and later explore the short lasting phenomena which affect the change of electron density it is necessary to determine a procedure which will effectively identify the phenomenon according to its duration as a desired input parameter. Known mathematical and programming tools are used in the parameter analysis and they will be explained in detail later on.

II. Definition and Structure of the Ionosphere

The Earth's Atmosphere is under influence of many natural processes that cause changes of the chemical and physical characteristics of each layer. In addition Atmosphere is under constant influence of solar and cosmic radiation which represent major factors of frequent changes in atmosphere layers. Such changes and mutual interdependency of the Earth Atmosphere layers characterize Earth's Atmosphere as frequently changing and unstable environment.

From telecommunications perspective, atmosphere is used as a medium and it is frequently a subject of many scientific and research papers [2]. In order to better understand the specific characteristics of the Earth's atmosphere and its layered structure and how the changes in Earths atmospheres influence radio signal propagation, different parameters have been devised such as the following: dielectric constant, electron density specific for each layer individually and those that originate from them due to ionization, refractive index - which depends on electron density and geomagnetic field.

Based on those parameters, it is possible to create a model which spatially and time-wise describes the propagation of electromagnetic waves [3].

Ionosphere is a layer whose charged particle density significantly influences the propagation of the electromagnetic waves. As mentioned ionosphere consists of 3 layers: D- layer, E- layers i F- layer. D-layer is the lowest one, and its characteristics above 70 km are influenced by solar radiation the most, which explains why it exists only during the day. During the night, at these heights cosmic radiation is the only source of ionizing radiation which influences the D-layer which is not enough for its existence [1]. Concerning the propagation of the electromagnetic waves, this layer reflects very low frequency waves (VLF/LF), while high frequency waves pass through this layer attenuated.

Like the previous one, E-layer exists only during the day. It is formed when solar X-ray flux is high enough to ionize the proper neutral particles. For the purposes of telecommunications the emergence of sporadic E-layer (E_s) is significant. E_s lasts for a short period of time and is considered to occur as a consequence of solar activity and lightning [4].

The F-layer is characterized by nonhomogenic chemical composition during the day which is why in that period it is divided into two sub layers: F1 and F2 sub layer. Each of these sub layers is influenced by different types of radiation, which can lead to the occurrence of multiple deflections from each of the sub layers individually, especially in such a way so that, during the propagation of the electromagnetic waves on certain distances, the radio signal is not even detectable on Earth due to its retention in a temporary waveguide (a phenomenon known as Ducting) [5, 6, 7, 8]. During the night, F1and F2 sub layers are combined and make up the F-layer. High frequency electromagnetic waves are reflected off this layer [9].

All radiation waves which get into the atmosphere are spatially and time-wise variable. Besides solar radiation, the influence of natural phenomena, such as lightning, represent a considerable factor in analyzing changes in ion density in D-layer of the Ionosphere. During the last couple of decades the changes in the ionosphere are influenced through human activity (rapid development of technology and industry, the human influence on the ionosphere is increasing). Recent scientific research has provided results which indicate increasing influence of nuclear and strong chemical explosions on atmospheric particle density [10, 11].

Concerning telecommunications, the most significant parameter of the ionosphere is electron density (N_e) which is used to calculate electron plasma frequency (w_p):

$$w_p = \frac{4\pi N_e q_e^2}{\varepsilon_0 m_e} \qquad (1)$$

Where q_e is the elementary charge, ε_0 the medium permittivity and m_e the mass of an electron. Electron density increases with the increase of altitude. Ionizing radiation, solar flares and γ-ray bursts can all affect electron density. Lightning exerts the most significant influence of the lower layers of the atmosphere and on D-layer parameters. The most significant consequences of this natural phenomenon are ionization and warming. Lightning also causes the creation of quasi-electrostatic field, whose presence can trigger an array of other disturbances [12]. The causal link of natural phenomena proves the complex nature of the Earth's atmosphere as well as the complexity of its research.

The analysis of the electron density in the D-layer of the ionosphere is based on the theory of the propagation of the VLF/LF electromagnetic waves. During the propagation of the VLF/LF radio signals, the amplitude of their surface component is equalized with the noise level and becomes undetectable [2]. Unlike the surface component, the spatial component of VLF/LF radio waves reaches the D-layer of the ionosphere where it is reflected back to the Earth's surface where it is once again reflected and returned to the atmosphere. The space limited by the D-layer's upper border layer on one end, and the Earth on the other is treated as a waveguide in the analysis of the propagation of the radio wave of this frequency. The electromagnetic field which comprises of the individual spatial components (mods) is registered by an adjusted receiver. It is exactly this method of measurement that enables us to conduct the analysis of nonperiodic and short lasting D-layer changes from the Earth's surface.

III. EXPERIMENTAL SETUP AND THE ANALYSIS OF ELECTRON DENSITY IN THE D-LAYER

Layered analysis of the D-layer is possible because of the widespread VLF transmitters and receivers. There are several of international networks, some of the best known being: AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education), AARDDVARKK (Antartic-Artic Radiation-belt (Dynamic) Deposition – VLF Atmospheric Research Konsortium) and SAVNET (South America VLF NETwork).

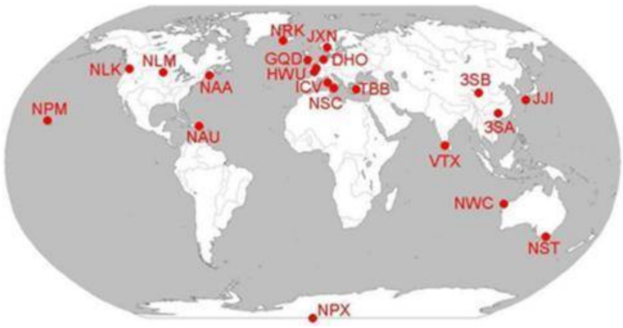

Figure 1. AWESOME transmitter map [13]

The receiver used for the purpose of this paper is a part of Stanford/AWESOME (Figure 1 and Figure 2) network which is located in the Institute of Physics in Belgrade.

Figure 2. AWESOME receiver map [13]

Intense radiation which causes significant changes of the amplitude and phase of the VLF signal and originate from the Sun and the space are easily detectable and noticeable during the analysis. In the case of lower intensity radiation and changes considered to cause insignificant variations in electron density various statistical methods and transformations have been utilized.

The post-processed receiver data has been recorded as day-long measurements in individual files with the .mat extension for the purposes of further processing and analysis using Matlab software (as one of the programs compatible for further analysis).

The first problem to be solved using Matlab was related to loading the data from .mat files, (eleven representative days of measurement (Figure 3)).

```
d=dir('*.mat');
x=[];
for i=1:length(d)
x=[x; load(d(i).name)];
y(i).data=x(i).data;
end
```

Figure 3. Code section used for loading .mat files

The data contained inside mentioned .mat file is comprised of many data records from which the received signal level was to be filtered out. Figure 3 shows that the values of the received signal amplitude are assigned to matrix y. For the purposes of further processing it was necessary to define the time interval depending on the phenomena of interest. For example, if we want to observe the influence of short lasting phenomena, such as lightning, we will use the shortest time interval possible, which, in a limiting case can be reduced to 20ms, which is the recording resolution of the mentioned parameters.

It was also necessary to define the signal level which can be considered an error, i.e. made under the influence of human factor. On two occasions there was no reception which caused gaps in data records and further complicated processing of the data and detailed analysis (Figure 4). The cause of these gaps is the fact that the transmitter stops working for an hour in the morning, while the receiver stops working for an hour in the afternoon.

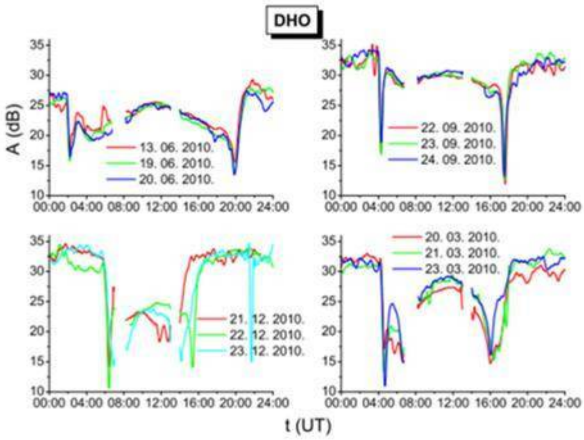

Figure 4. Received signal levels and “gaps” created by the discontinuation of the receiver’s and transmitter’s operation [2].

A more detailed analysis of the phenomena of interest, whose duration interval covers a larger portion of the day, required the gaps to be filled with adequate data, so that the measured signal can be represented with a fitted function, which authentically displays the daily change trend, as accurately as possible. In the beginning all the received signal’s amplitude values are loaded. Each of these values is compared to the defined minimum and if the level of the received signal value is lower, its value is increased by one tenth of the previous one. In this manner it is possible to eliminate the problem in the program loops’ operation, so that the „NaN“ values are assigned real values which could later be used in processing. In this manner, regarding the short lasting phenomena which affect the change in the electron density of the D-layer, the time period in which there was no measurement was defined as „calm state“, but in later analysis retained detectability with the linear manner of its amplitude’s increase. When the values of the amplitudes are examined, a matrix in which all gaps are populated is obtained. In order to define the phenomenon of interest, for the purposes of detection it is necessary to enter the time frame in which the expected phenomenon is registered as an input parameter. For detection purposes, as well as increased detection speed, averaging in the interval defined by the time frame is performed in order to compensate for the high measurement resolution which causes large quantities of measurement data. In order to obtain the average value, the „mean“ function is used (Figure 5).

```
for i=1:length(y)
    for j=1:length(y(i).data)
    if y(i).data(j)<minimum
        y(i).data(j)=y(i).data(j-1)+0.1;
    else
    end
        usrednjeno(i,:)=mean(y(i).data,prozor);
    end
end
```

Figure 5. Code section which compensates for the lost signal values and calculates the average value of the given time frame

The next step in processing was fitting – approximation of the measured data with a function which most accurately depicts the timewise change trend of the measured data. Fitting is done so that, using the obtained results, after averaging on the time interval defined by the time frame which defines the expected time interval of the subject phenomenon, a function, whose later analysis of the extreme value and inflection points can be used to automatically identify the phenomena in the large amount of data acquired by measurement, can be provided. In this manner further analysis becomes simpler, while the time needed for the subject phenomenon detection is significantly reduced. Matlab provides a large number of functions used for fitting. For the analysis described in this paper the choice narrows down to two: fitting using a polynomial of a certain degree and fitting using a Fourier series with a specific number of coefficients. The former is implemented by function „polyfit“. The function requires three arguments the first of which is a vector which contains data based on which the fitted function is created. The second parameter defines the data interval in which fitting is conducted. Depending on the phenomenon whose influence on the D-layer is observed, the interval is defined as a number of points of measurement in accordance with the already defined time frame. The last parameter provides the degree of the polynomial which is used to represent the requested function.

```
for i=1:length(y)
    for j=1:length(y(i).data)
        t(i)=[1:m(i)];
        z(i)=fit(t(i)',usrednjeno(1,j)','fourier8');
        y=polyfit(usrednjeno,t,5);
    end;
end;
yprim=polyder(y);
plot(t,usrednjeno(i))
hold on;
plot(z(i),'r');
```

Figure 6. Code section performing the averaging of the function in the given time frame

Using this type of approximation the values, which would be satisfactory for short lasting changes are not obtained. Their similarity to the measured values is incresed in accordance with the increase of the function degree. Because of that, the procedure of forming a Fourier series proved to be the adequate method of detecting phenomena whose duration is approximately one minute. After obtaining the results using this method, it was observed that they were considerably more accurate than those obtained by the previouse one and that this method required a function of a considerably lower degree. The shortcoming of averaging using a Fourier series is reflected in the fact that the obtained results are considerably more difficult to process compared to those obtained by fitting using a polynomial.

IV. CONCLUSION

This paper depicted an automated procedure of identifying a phenomenon which causes a disturbance in the D-layer electron density. Considering the large quantity of data obtained by recording via a receiver of a high time resolution, it was necessary to identify and separate the phenomenon in question in the large quantity of data for the purposes of later analysis. The described procedure is universally applicable to an array of measured data in which inconsistency is present (so called measurement gaps), where data can originate from any source used for detecting nonperiodic changes of the measured quantity.

The general shortcoming of this procedure is processing time. The analysis of data contained in eleven files each containig two million recordings in average, using a workstation with an Intel Core i7 4710HQ processor and with 8GB RAM took approximately 48 hours. An attempt has been made to compensate for this by code optimization, using fewer loops, but this exercise did not result in significant improvement in processing time.

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