ACTA TECHNICA NAPOCENSIS
Electronics and Telecommunications

LOW-COST PROTOTYPE EQUIPMENT FOR VLF RADIO WAVE MONITORING

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Abstract: The paper presents a short overview of the natural phenomena that generates VLF, ELF and SLF electromagnetic waves. In order to emphasize the importance of studying these waves, the paper presents a prototype equipment used for receiving and monitoring very low frequency electromagnetic waves generated by natural and artificial sources. The functionality of the equipment is proved by monitoring, during several days, different VLF radio transmitters located at distances over 1000 km from the reception point. The data collected revealed the diurnal variations of the VLF radio wave propagation and the induced disturbances in propagation conditions during January 4th 2011 partial solar eclipse.

Keywords: *radio wave propagation, ionosphere, VLF, low noise amplifier*

I. INTRODUCTION

The study of very low frequency electromagnetic waves involves an interdisciplinary study that requires vast knowledge of physics, astronomy, geophysics and electronic engineering. The analysis of EM waves below 30 kHz can provide important information in areas like Meteorology and Climatology, Physics of high Atmosphere and Astrophysics, Geophysics and Seismology or Special Telecommunication.

In this part of the spectrum, the reception of these waves is difficult because in most cases the SNR values are very small. In order to improve the SNR, is necessary to use specialized sensors which are usually frequency dependent. Also, it requires to use sampling techniques and computer-assisted spectral analysis for online and offline processing of the received signal. Large urban areas are heavily polluted by electromagnetic power generated by the power distribution networks, by industry and home consumers. In order to get useful data, it is necessary to make experimental tests in a remote location.

According with NTIA Department of Spectrum Management [1], electromagnetic waves below 30 kHz are known as Very Low Frequency electromagnetic waves and those below 3 kHz are not assigned to any civil activities. In Europe, the frequency allocation table for various commercial, scientific or military activities starts from 9 kHz. Bellow this value, the frequency bands are not protected by legislation and radio monitoring [2].

In scientific papers, low frequency electromagnetic waves are divided, according with the frequency domain, as follows: Very Low Frequency (VLF): 30 kHz – 3 kHz; Ultra Low Frequency (ULF): 3 kHz – 300 Hz; Super Low Frequency (SLF): 300 Hz – 30 Hz.

I.1. Very Low Frequency EM waves generated by meteorological phenomena

Electrical discharges in the atmosphere (lightning) made by tropical storms generates wide spectrum electromagnetic waves. Usually, for very low frequency EM waves, the space between the Earth's surface and the ionosphere acts as a waveguide through which they propagate over long distances, and sometimes surrounding the entire Earth. The analysis of these waves is important in the climatology field, because you can get a global picture of the meteorological local phenomena [3].

The electrical discharges that occur during severe storms generate ULF and ELF electromagnetic waves, which can produce an electromagnetic resonance called Schuman resonance. The Schuman resonance (7.83 Hz, 14.3 Hz, 20.8 Hz, 27.3 Hz or 33.8 Hz) was predicted by Winfried Otto Schuman in 1952. These frequency resonance values are not fixed because they are influenced by weather conditions and solar-induced perturbations, that lead to changes into ionosphere, consequently to the volume of the "resonance box". The strength of the resonating EM waves depends on the number of lightning that occur in a period of time. The experimental results illustrated that during one day, there are 3 periods of maxim activity: one corresponding for the South-East Asia tropical storms, after 5 hours corresponding for the storms in Africa, and after another 6 hours, corresponding for the South America storms [4]. The scientific analysis of this phenomenon may provide important information regarding the global climate changes and even in the climatology field.

I.2 Very Low Frequency EM waves generated by "space weather"

The so-called "outer space weather phenomena" such as solar flares, rain of meteorites, major flows of elementary particles or different source radiations, generate VLF, ULF and SLF EM waves. However, the solar activity is the main factor in generating electromagnetic phenomena on a planetary scale, through the high energy cosmic rays and particles of the "solar winds", especially during high period of solar activity.

Manuscript received October 29, 2011; revised December 17, 2011

Earth's magnetic field is a natural shield against the solar wind, cosmic radiation and other very high energy particles. Strong solar flares can generate electromagnetic storms during which the Earth's magnetosphere is strongly disturbed. In Polar Regions, where the magnetic field intensifies and the filled lines are open, many high-energy electrons penetrate up to altitudes of the order of 100 km and interact with the gas molecules in the atmosphere. Through this interaction a large amount of photons is released. This phenomenon intensifies during electromagnetic storms and is often visible from Earth in the form of aurora borealis. In these regions, the electric current generated by electric charges can reach values of one million amps in a relatively small area.

If the electromagnetic storm is very intense, the aurora phenomenon can occur at lower altitudes, as observed on July the 15^{th}, 2000 in southern of France. Strong electromagnetic storms can have disastrous effects on telecommunication and navigation equipment or on aircrafts. Also, large variations of the magnetic field can induce strong currents in the electric power lines which cannot be compensated for. In 13^{th} of March 1989, a strong magnetic storm caused the collapse of the electric distribution system in the southern of Canada and United States for nine hours.

I.3. Very Low Frequency EM waves generated by the tectonic activity

Earthquakes appear due to the activity within the deep crust of the Earth, in areas of transition between different tectonic plates and have a catastrophic effect at the surface of the Earth. Many crystalline materials, subdued to mechanical pressure and distortion, generate an electric field through the piezoelectric effect. The friction between two poor conductor bodies causes a displacement of electric charges which results in the appearance of an electric shield. The triboelectric effect together with the piezoelectric effect that occurs in the deep crust of the continental or transcontinental tectonic plates generates intense electromagnetic waves [5].

The rock layers are opaque to electromagnetic waves and they are rapidly attenuated when are generated in deep crust. In contrast, very low frequency electromagnetic waves (tens of Hertz or less) propagate within the rock layers much faster and have less attenuation [5]. In recent years, geophysicist began to give an increasing importance to the interdependence between the magnitude of earthquakes and the emission of very low frequency EM waves by placing sensors in regions with high seismic risk and analyzing data recorded before and after the telluric movements. The Loma Prieta (1989), Kobe (1995) or Aquila (2009) earthquakes were accompanied by electromagnetic precursor phenomena and have been highlighted as indubitable recordings [6]

This increasing of very low frequency EM waves appears hours before a devastating earthquake and grows rapidly with few minutes before the telluric surface movement. Also, the ionization of the atmosphere can occur, giving the impression of forming of aurora borealis, even if the events occur somewhere over the Poles. Experimental highlighting of these EM waves is very difficult and requires highly sensitive special equipment. The cost of a system like that is very high given the fact that the monitoring sensors must be working day and night for decades, awaiting a devastating earthquake. In Romania, one of the major project developed by INFP consist in finding a connection between the seismic precursors and seismic movements [7]. The project developed by Advanced National Seismic System (USA) in collaboration with Swiss Seismological Service, publishes daily, for the next 24 hours, a seismic prediction map similar with the isothermal and isobaric maps used in meteorology. This map illustrates the probability of major earthquakes in various regions in California. [8]

I.4. Very Low Frequency EM waves generated by human activities

VLF radio transmitters that operate into frequency range 9 kHz – 90 kHz, are used to ensure a direct radio link with civil and military vessels The US armed forces developed a system called Project ELF (Seafarer), for transmitting information to the fleet of submarines that are in submersion. The system was operating on a 76 Hz with two antennas, one located in Clam Lake, Wisconsin and the other one in Republic, Michigan [9]. The ZEVS system developed by Russian Navy operates at a frequency of 82 Hz with the transmitting antenna located in Kola Peninsula, near Murmansk (far north of Russia). Other artificial very low frequency EM sources are associated with ELF/VLF ionospheric heating experiments [10,11,12].

II. VLF RADIO WAVE PROPAGATION

Long distance propagation of VLF radio waves is improved due to the reflection by the F Layer (200-250 km altitude) and is diminished by the absorption of the radio waves, passing through D and E layers of the ionosphere (60 – 150 km altitude) [13]. Due to the photoionization effect, the density of the ions within the E layer of the ionosphere is higher during daytime than at night. During the daytime, the ionization process in the D layer is low, because it is the lowest region of the ionosphere (60 – 90 km altitude). After the sunset, the positive ions are recombined with the free electrons within D and E layers, resulting in the disappearance of the D layer and the reduction of the ions density in the E layer.

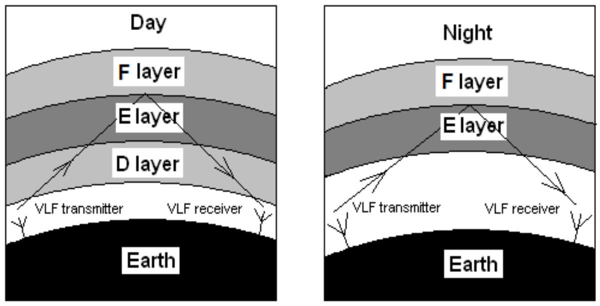

Figure 1. Long distance VLF radio wave propagation

This results in the decrease of absorption rate for the radio waves passing through this layer. Due to this phenomenon of ionization and recombination of the ions, long distance propagation of the VLF radio waves is favored during the night and not during the daytime. Long distance VLF propagation mechanism is illustrated in Figure 1.

III. THE MONITORING SYSTEM

The monitoring of the VLF radio waves was possible using a low-cost prototype receiving equipment. The block diagram of the VLF monitoring system is presented in Figure 2.

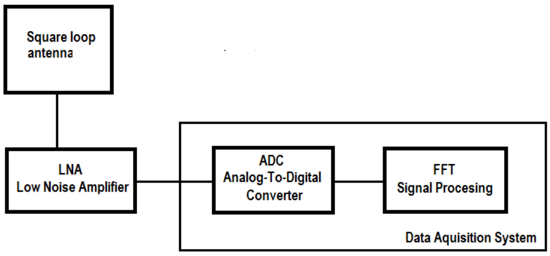

Figure 2. Block diagram of the VLF monitoring system

The square loop antenna has 33 turns of insulated copper wire with a section of 1.5mm^2, placed on a 0.7 m side framework. The effective receiving area of the antenna is approximately 16m^2. The structure of loop antenna is presented in Figure 3.

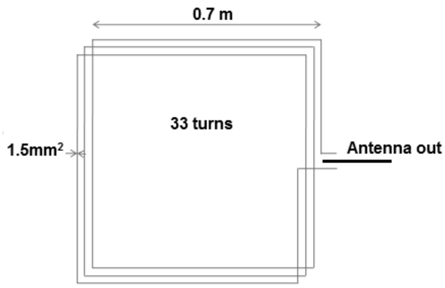

Figure 3. Aerial VLF loop antenna

The low noise amplifier (LNA) is based on the low noise Burr-Brown's INA116 analog chip [14], especially used for instrumentation. The basic electrical scheme of the LNA is presented in Figure 4. The input impedance of the amplifier is Z_{in}=1.2kΩ and with a voltage gain of A_u=30dB. The data acquisition block consists of a 24bit high resolution analog to digital converter (ADC) and a signal processing software application (Matlab, SpectrumLab, Spectran), especially designed for FFT analysis of VLF signals.

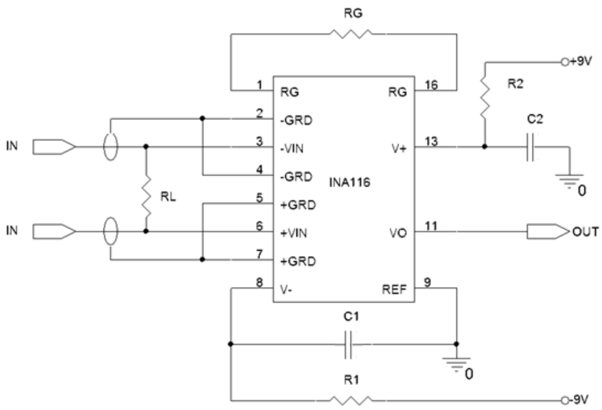

Figure 4. Low-Noise Amplifies wiring diagram

A similar device was developed by the researchers from Stanford University [15] and is designed for VLF radio wave monitoring and studies regarding the sudden ionosphere disturbances. The VLF monitoring equipment was installed in Marisel, Romania.

III.1. The monitored VLF transmitters

During December 2010, for several days, a VLF monitoring in the frequency range 17 kHz – 24 kHz was performed, using the low-cost prototype equipment described above. The FFT analysis software application Spectran is configured in "waterfall" mode for online processing of the received VLF signals. After analyzing the data obtained it was found that:

- Five VLF stations, which operate on regular basis, were identified, based on information obtained from the VLF worldwide community.
- All the VLF stations have periods of interruption of transmission, probably for maintenance reasons. For example, the DHO38 VLF station, placed in north of Germany, has predictable daily interruptions of the transmission, between 07:00 UTC and 08:00 UTC.
- There are other unknown operating VLF stations, which were not identified by its call sign.

Figure 5 presents the VLF received signals on February 16th 2011. The noise level is around -110 dBm. You can observe VLF stations with different SNR values depending on the distance between the stations and the reception point, the transmitting power and the propagation conditions. The most important and known VLF stations are presented as follows:

- 19.6 kHz – GBZ British submarine communication station located in Anthorn, England.
- 20.27 kHz – ICV NATO Naval communication station located at Isola di Tavalora, Italy.
- 20.5 kHz – RJH69 Russian time station located in Molodechno, Belarus.
- 21.75 kHz – HWU French Navy communication station located at Rosnay, France.
- 23.4 kHz – DHO38 NATO German Marine located in Rhauderfehn, Germany.

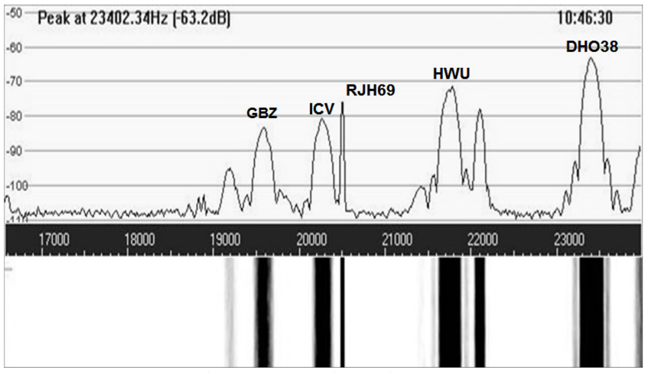

Figure 5. Received VLF signals with Spectran software in "waterfall" mode

Figure 6 illustrates the location of the points of interest and the radio path length related to the observer's location.

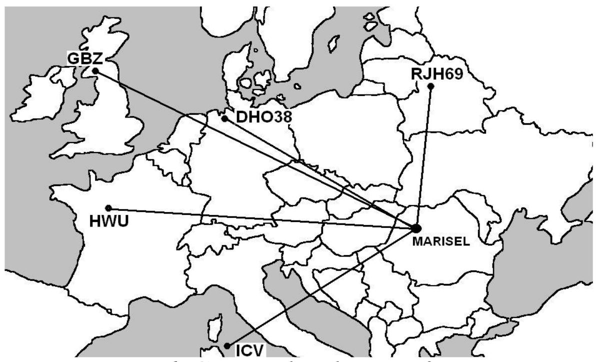

Figure 6. Geographical point of interest

IV. EXPERIMENTAL RESULTS

All the preliminary experiments took place in winter time, when the interference produced by the atmospheric discharges is minimal. During the period of time December 2010 and February 2011, a long distance monitoring of the 23.4 kHz DHO38 transmitter (placed near Rhauderfehn, north of Germany) was made.

The main reason, in choosing the DHO38 VLF transmitter, is that the distance between Cluj-Napoca and the DHO38 location is large (1400 km), meaning that the level of the signal reflected by the ionosphere is high. Also, this VLF transmitter is monitored continuously by Stanford's Space Weather Monitor Program and all the related data from different monitoring locations is available for scientific community [15]. The geographical coordinates of the VLF transmitter and the reception point are presented in Table 1.

Location	Latitude	Longitude
MARISEL	46˚41'N	23˚07'E
DHO38 (23400Hz)	53˚05'N	7˚37'E

Table 1. Geographical coordinates for the point of interest

Figure 7 illustrates the 24-hour monitoring DHO38 VLF received signal, between 16th of January 2011 (12:23:37 UTC) and January 17th 2011 (12:34:35 UTC). All the measurements were made automatically at regular intervals of 11 seconds. The 24-hour monitoring consists of more than 7900 measurement points.

The offline processing of the data collected revealed diurnal variations of the electromagnetic propagation conditions due to the changes in the lower layers of the ionosphere. Note that VLF wave propagation is favored during night time and not during daytime. Also, it is highlighted how the conditions of propagation deteriorates during sunrise and sunset. The most important points and periods of time are presented as follows:

- A – The beginning of the monitoring period.
- B – The moment of sunset (15:53 UTC) in relation with the reception point (Marisel).
- C – The moment of sunset (16:42 UTC) in relation with the transmission point (DHO38).
- D – The moment of sunrise (05:31 UTC) in relation with the reception point (Marisel).
- E – The moment of sunrise (6:44 UTC) in relation with the transmission point (DHO38).
- F – The moment of interruption (6:59:02 UTC) of the DHO38 VLF transmitter.
- G – The period of time (07:35 – 07:40 UTC) when the DHO38 VLF transmitter was ON for a short time.
- H – The moment of time (08:04 UTC) when the VLF station started to normal operation.
- I – The end of monitoring period.

The received signal strength (between CD section of the graphic) is greater (approximately 10 dB) than the signal received during daytime (intervals AB, DE and HI).

During the sunset period of time (sunset corresponding to the transmitting and reception point) the received signal strength has a slightly decrease in power, followed by a significant increase. Also, during the sunrise period of time (sunrise corresponding to the transmitting and reception point), the received signal strength has strong decrease in power, followed by a rapid increase.

Also, the graphic illustrates sudden and short increases of the received signal followed by sudden decreases. These spikes (located between CD and HI sections) are caused by electrical equipment disturbances located near the reception point.

The period of time related with these spikes, can last from five minutes up to tens of minutes, which suggests human disturbance activities. This kind of monitoring of a specified frequency may be useful also for identifying locations with reduced VLF electromagnetic pollution.

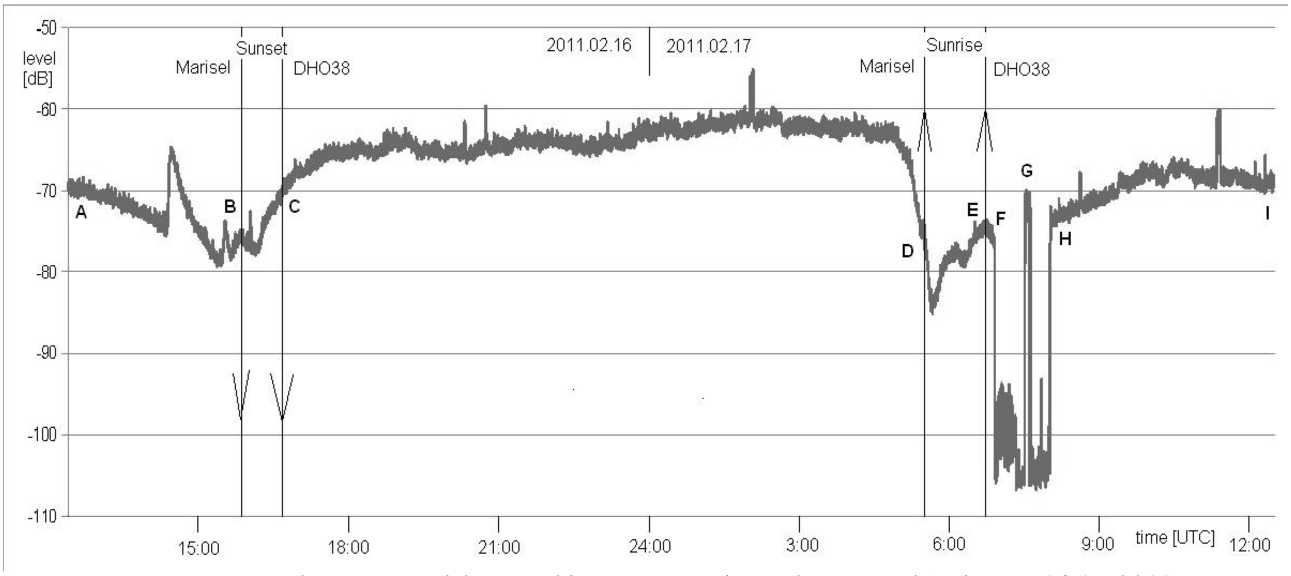

Figure 7. Diurnal variations of the DHO38 VLF received signal in Marisel (February 16-17, 2011)

The experimental equipment also collected data during the partial solar eclipse on January the 4th 2011 and highlighted the induced disturbances in VLF radio wave propagation [16]. Figure 8 presents a comparison between the evolution of the signal received from the DHO38 VLF transmitter during the partial solar eclipse of the Sun and the day after.

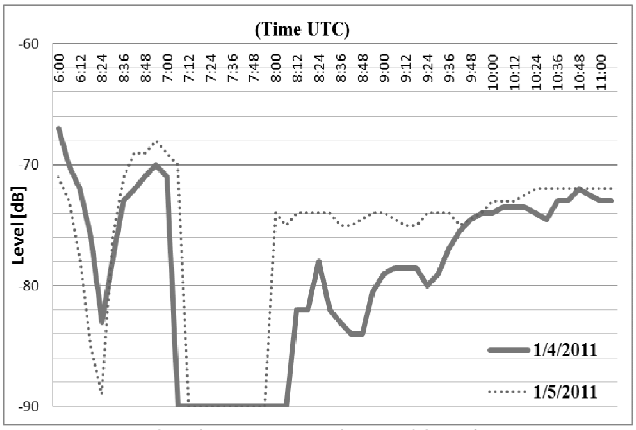

Figure 8. Fluctuations of DHO38 radio wave propagation comparison

V. CONCLUSIONS

By using low-cost prototype receiver equipment, you can emphasize changes in the propagation conditions for VLF electromagnetic waves. These changes occur due to diurnal variations within the ionospheric layers and the sudden ionospheric disturbances. The hardware equipment described in this paper also highlights propagation disturbances of DHO38 VLF signal, during the partial solar eclipse on January 4th 2011. The low-cost monitoring system is ideal in university environments for illustrating long distance VLF radio wave propagation and encourages formation of a coherent education student community.

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