FDTD Computation for Schumann Resonance on Martian surface

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ABSTRACT

In a planetary environment, an electrical conductivity of ionosphere and ground create a spherical electromagnetic cavity. In this cavity, extremely low frequency, i.e. 3-3000 Hz electromagnetic waves are weakly attenuated and can propagate around the globe, producing global resonance. The extremely low frequencies are generated by electric discharges in planetary atmosphere. Dust devils exist on the Mars surface due to the temperature variation. The electrical discharges are expected to occur within the Martian dust devils. Natural electromagnetic waves are generated near the surface due to electrostatic discharges in the dust devils, which could be trapped in the resonant cavity of Mars. This can give rise to Schumann resonance in the Martian environment. The finite difference time-domain technique may be employed to model the global lightning activity in atmosphere of Mars to study the Schumann resonance. In this paper, we have implemented one dimensional finite difference time-domain technique to understand the Schumann resonance in the Martian environment. The simulation results and analysis are given, which may be helpful to understand initially the possible lightning on the Mars.

Keywords - Schumann Resonance, Wave Propagation, Lightning on Mars, Maxell's equation

1. INTRODUCTION

The conducting surface of a planet and the conducting lower ionosphere form a concentric cavity, the earth-ionosphere cavity. The electromagnetic waves are trapped in this cavity. These electromagnetic waves are produced by lightning discharges. The extremely low frequency (ELF) i.e. 3-3000 Hz signals can travel around the earth without suffering much attenuation and produces resonance. On Earth, such resonances are referred to as Schumann resonance and are excited by lightning discharges. The detection of such resonances on other planets may support the Existence of the lightning discharge on the lower atmosphere of these planets. The tool to obtain Schumann frequency modes is Finite difference time-domain technique (FDTD). The paper mainly focuses on a three dimensional finite difference time-domain technique is employed to study the Schumann resonance for possible lightning on Mars[1].

The existence of electrical discharges generated by storms on Mars is suggested by Crozier, and lithosphere activity is likely to be accompanied by electrical discharges. Martian atmosphere shows some weather activity such as clouds and wind dynamics, but the requirements for lightning generation are not determined yet. If such discharges exist, the extremely low frequency fields (ELF, 3-3 kHz) would couple in the resonant cavity constituted by the Martian lithosphere and ionosphere to give rise to Schumann resonances on Mars. Dust devils are expected to be a source for lightning activity on Mars. Martian dust devils can be up to fifty times as wide and ten times as high as terrestrial dust devils [2].

The finite difference time-domain method involves discretization of the Maxwell's equations in both time and space. FDTD is combined with signal processing techniques to provide an efficient numerical tool to analyse the electrical conductivity profile of the Martian atmosphere, with the aim of calculating the resonance frequencies. The main advantage of a finite difference time-domain model is its flexibility and simplicity to introduce an arbitrary conductivity profile [3].

The Schumann frequency mode is obtained using Fast Fourier Transform (FFT) method. The Software used is MATLAB, which is most convenient for the solutions of the problem that are robust. Fast Fourier Transform method essentially states that the frequency content of any signal can be described as the sum of a specific set of sine waves. The Fourier transform is one of the most commonly used methods of signal analysis. It is simply a mathematical transformation that changes a signal from a time domain representation to a frequency domain representation thereby allowing one to observe and analyze its frequency content. Plotting a Fourier transform gives us a visual representation of the relative proportion of different frequencies in an input signal. So, FFT is most convenient to obtain Schumann frequency mode.

2. SCHUMANN RESONANCE

Schuman properties for the earth-ionosphere cavity were theoretically predicted by W.O. Schumann. The first observation of the global electromagnetic resonance problem was carried out in 1952 by W.O. Schumann, and the phenomenon is regarded as the Schumann resonance. The Schumann Resonances are standing wave i.e. electromagnetic waves that exist in the earth-ionosphere cavity. Like waves on a spring, they are not present all the time, but have to be 'excited' to be observed. They are not caused by anything internal to the Earth, its crust or its core. They seem to be related to electrical activity in the atmosphere, particularly during times of intense lightning activity. They occur at several frequencies between 6 and 50 cycles per second; specifically 7.8, 14, 20, 26, 33, 39 and 45 Hertz[6]on Earth. So long as the properties of Earth's electromagnetic cavity remain about the same, these frequencies remain the same. Observations of Schumann resonances have been used to track global lightning activity. Owing to the connection between lightning activity and the Earth's climate it has been suggested that they may also be used to monitor global temperature variations and variations of water vapour in the upper troposphere [6].

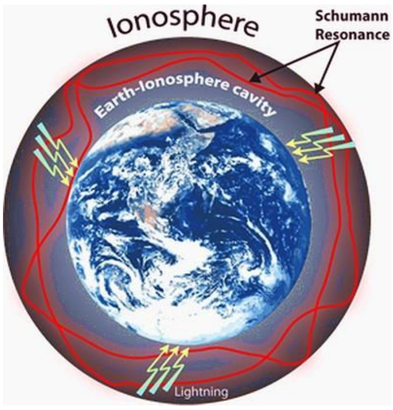

Figure 2.1 Earth-ionosphere cavity and Schumann resonant[7]

Lightning discharges are considered to be the primary natural source of Schumann resonance excitation. These lightning channels behave like huge antennas that radiate electromagnetic energy at frequencies below about 100 kHz. These signals are very weak at large distances from the lightning source, but the Earth–ionosphere waveguide behaves like a resonator at ELF frequencies and amplifies the spectral signals from lightning at the resonance frequencies. In an ideal cavity, the resonant frequency of the nth mode fn is determined by the Earth radius 'a' and the speed of light 'c'[5]

$$f_n = \frac{c}{2\pi a}\sqrt{n(n+1)} \qquad (1)$$

At any given moment about 2,000 thunderstorms roll over Earth, producing some 50 flashes of lightning every second. Each lightning burst creates electromagnetic waves that begin to circle around Earth captured between Earth's surface and a boundary about 60 miles up. Some of the waves - if they have just the right wavelength - combine, increasing in strength, to create a repeating atmospheric heartbeat known as Schumann resonance [8].

2.1 Wave Propagation and lightning on Earth

Wave propagation at the bottom of the electromagnetic (EM) spectrum (below 300 kHz) in the Earth-ionosphere system is a problem having a rich history of theoretical investigation extending over many decades. Propagation within this system involves complex interactions of EM waves with the lithosphere, oceans, and ionosphere, leading to resonances that involve literally the entire planet Earth. Currently, EM phenomena below 300 kHz form the physics basis of remote-sensing investigations of lightning and sprites, global temperature changes, subsurface structures, submarine communications, and potential earthquake precursors[9].

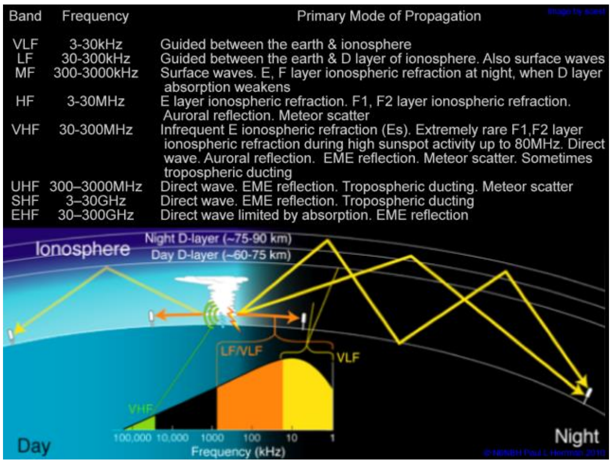

Figure 2.2 Schematic diagram of the Earth-ionosphere wave guide[10]

The Earth can be regarded as a nearly conducting sphere, wrapped in a thin dielectric atmosphere that extends up to the ionosphere, for which the conductivity is also substantial. Atmospheric electric discharges generate broadband electromagnetic waves that propagate between the surface and the lower boundary of the ionosphere (~100 km). These two layers define the surface-ionosphere cavity, which supports both longitudinal and transverse electromagnetic modes. Lightning, most frequent over continents, particularly at low latitudes, induces the development of standing waves, whose wavelength is related to the radius of the cavity[11].

The Schumann resonance (SR), predicted by Schumann [1952], is believed to originate from electromagnetic emission, generated by the lightning activity in the Earth-ionosphere cavity. At ELF frequencies there is a very small attenuation, which allows electromagnetic waves to propagate even a few times around the globe before dissipating. Standing waves generate the constructive interference at 8, 14, 20 ...Hz[11].

The Schumann Resonances are located in the ELF (Extremely Low Frequency) and SLF (Super Low Frequency) range of the EM spectrum. This range is from 3Hz - 30Hz and 30Hz - 300Hz respectively. The surface of the earth and the ionosphere create a spherical cavity that has a resonant frequency. These resonances are naturally excited by the thousands of lightning strikes occurring every second around the planet. High altitude nuclear bomb detonations also artificially excite these resonances to high levels for short periods of time. This is how the resonances were first physically detected. Experimenting equipment detected them during high altitude nuclear burst testing in the 50s. If one takes the speed of light in kilometers (300,000 Kms) and divides it by the circumference of our planet in kilometers (40,000 Kms) one ends up with 7.5. This number is in cycles per second so one could predict that the base resonant frequency is near 7.5Hz[11].

2.2 Lightning on Mars

Mars is similar to Earth in many ways, having many of the same "systems" that characterize our home world. Like Earth, Mars has an atmosphere, a hydrosphere, a cryosphere and a lithosphere. In other words, Mars has systems of air, water, ice, and geology that all interact to produce the Martian environment[12].

Figure 2.3 Mars [12]

Mars is one of the few remaining planets in the Solar System where lightning has not yet been detected. But there is evidence on the planet that suggests the presence of lightning, such as signs on the ground of potential lightning strikes or the formation of particles in the soil examined by Viking landers that could be explained by lightning discharge. Still, there haven't been any direct observations or confirmations yet. The most direct evidence so far came through observations conducted in 2006. That search found indications of lightning in radio waves that corresponded to dust storms occurring on the planet at the same time. Both searches used a combination of special techniques to try and capture a glimpse of Martian lightning. Calculating the Schumann resonances for the cavity between the Martian surface and ionosphere gives the specific frequencies at which we can expect to detect Martian lightning[13].

Figure 2.4 An illustration of a dust storm on Mars [14].

On the surface of Mars, electric discharges occur due to the dust devils present. Dust devils are basically the whirlwind. The whirlwind may be small or large in size. Due to the rise of hot air, dust devil carries the negatively-charged particles upwards and leaves the positively charged particles on the surface of Mars. Thus the charges get separated and will create the electric field. Electric field may then serve as a source for lightning to take place on the surface of Mars.

Figure 2.5 A speck of unexplained light may be seen flaring upwards from the hillside on Mars [21]

3. MODEL FORMULATION

3.1 Maxell's equation

Maxwell's equations are a set of partial differential equations that, together with the Lorentz force law, form the foundation of classical electrodynamics, classical optics, and electric circuits. Maxwell's equations describe how electric and magnetic fields are generated and altered by each other and by charges and currents[15].

Gauss law is given as,

$$\nabla \cdot D = \rho_v \qquad (2)$$

Guass magnetism law is given as,

$$\nabla \cdot B = 0 \qquad (3)$$

Faraday's law is given as,

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (4)$$

Ampere's law is given as,

$$\nabla \times H = \frac{\partial D}{\partial t} + J \qquad (5)$$

Maxwell's equations provide a description of electromagnetic phenomenon often mathematical difficulties are usually encountered while trying to solve the equations in the circumstances of practical applications. In a few special cases, it is possible to obtain exact analytic or approximate solutions. However in most cases of practical interest, numerical techniques are applied to obtain the approximate solutions. The finite difference time domain (FDTD) method is a full-wave and powerful numerical method for solving Maxwell's equations. The technique is one of the key simulation tools in study of electromagnetic propagation [16]

3.2 Finite Difference Time-Domain technique

Finite-difference time-domain is a numerical analysis technique used for modelling computational electromagnetic (finding approximate solutions to the associated system of differential equation). Since it is a time-domain method, FDTD solutions can cover a wide frequency range with a single simulation run, and treat nonlinear properties in a natural way[3].

The FDTD method belongs in the general class of grid-based differential numerical modelling methods (finite difference methods). The time-dependent Maxwell's equations (in partial differential form) are discretized using central-difference approximations to the space and time partial derivatives. The resulting finite-difference equations are solved in either software or hardware in a leapfrog manner: the electric field vector components in a volume of space are solved at a given instant in time; then the magnetic field vector components in the same spatial volume are solved at the next instant in time; and the process is repeated over and over again until the desired transient or steady-state electromagnetic field behaviour is fully evolved[3].

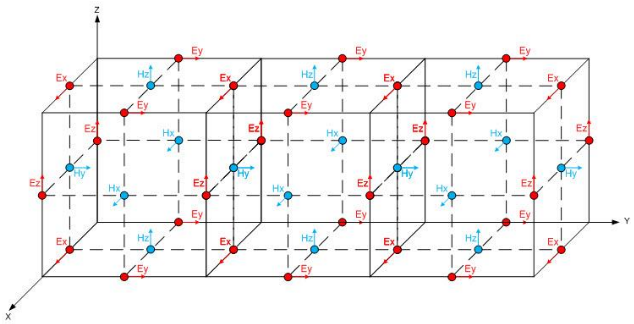

Figure 3.1 General Grid Cell Arrangement for FDTD

When Maxwell's differential equations are examined, it can be seen that the change in the E-field in time (the time derivative) is dependent on the change in the H-field across space (the curl). This results in the basic FDTD time-stepping relation that, at any point in space, the updated value of the E-field in time is dependent on the stored value of the E-field and the numerical curl of the local distribution of the H-field in space [3].

The H-field is time-stepped in a similar manner. At any point in space, the updated value of the H-field in time is dependent on the stored value of the H-field and the numerical curl of the local distribution of the E-field in space. Iterating the E-field and H-field updates results in a marching-in-time process wherein sampled-data analogs of the continuous electromagnetic waves under consideration propagate in a numerical grid stored in the computer memory [3].

The FDTD algorithms offer three primary advantages over previous analytical and frequency domain techniques:

First, FDTD can accommodate continuously varying parameters over the propagation path. In fact, FDTD can, in principle, permit straightforward modelling (with no increase in simulation time) of arbitrary geometrical and electrical horizontal as well as vertical inhomogeneities of the lithosphere and ionosphere. Previous methods do not offer this capability[18].

Second, Berenger states that although FDTD is more computationally demanding than frequency-domain mode theory, on-going improvements in computer resources will continue to decrease FDTD simulation times in the future. Cummer concludes that “the simplicity of FDTD propagation modeling and ever-increasing computer power [will] probably make FDTD the technique of the future[18].

Third, Berenger shows that FDTD “is more versatile than the waveguide method” because it can provide results for general wideband and impulsive applications. This finding is also supported by Cummer’s FDTD study of lightning, which shows that a “major strength” of FDTD is its automatic calculation of all the fields due to lightning discharge[18].

3.3 1D-Model

The theory on the basis of the FDTD method is simple. To solve an electromagnetic problem, the idea is to simply discretize, both in time and space, the Maxwell’s equations with central difference approximations. The originality of the idea of Yee resides in the allocation in space of the electric and magnetic field components, and the marching in time for the evolution of the procedure. To better understand the theory of the method, we will start considering a simple one-dimensional problem. Assume, at this stage, “free space” as propagation medium. In this case, Maxwell’s equations can be written as[19],

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu}\nabla \times E \qquad (6)$$

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon}\nabla \times H \quad (7)$$

where E and H are Electric field and Magnetic field vectors, respectively, μ is the equivalent magnetic current density and ε is the electrical permittivity.

In the one-dimensional case, we can use only E_x and H_y , (1) and (2) can be

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0}\nabla \times \frac{E_x}{\partial z} \quad (8)$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon_0}\nabla \times \frac{H_y}{\partial z} \quad (9)$$

that represents the plane wave in the z-direction.

Yee introduced a finite-differencing scheme for solving these equations. His formulation is the basis of what is now called the FDTD method. Today, the FDTD method is one of the most widely-used numerical methods for electromagnetic problems[19].

In the Cartesian coordinate system, if we assume the principle axes of the property tensors of the medium are aligned with the axes of the coordinate, that is,

$$\nabla \times E = -\mu\frac{\partial H}{\partial t} \quad (10)$$

The electric field and magnetic field in 1D can be obtained by the update equations in time given as[18]

$$\frac{H_y\Big|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y\Big|_{k+\frac{1}{2}}^{n-\frac{1}{2}}}{\Delta t} = -\frac{1}{\mu}\frac{E_x|_{k+1}^{n} - E_x|_{k}^{n}}{\Delta z} \quad (11)$$

$$\frac{E_x|_{k}^{n+1} - E_x|_{k}^{n}}{\Delta t} = -\frac{1}{\varepsilon}\frac{H_y\Big|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y\Big|_{k+\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta z} \quad (12)$$

The time varying electric field will generate a time varying magnetic field and the time varying magnetic field will generate a time varying electric field[18].

Figure 3.2 1D space-time chart of the Yee algorithm showing central differences for the space derivatives and leapfrog over the time derivatives, k represents electric field node numbers and n is the time step[18]

3.4 FDTD Computation

The atmosphere of Mars was first simulated as a perfect conducting cavity with no losses, i.e., a vacuum medium bounded by two concentric spherical surfaces; both considered as perfect conductors. The inner conductor was the surface of Mars whose radius is R_M=3390 km. The outer surface of the model was placed at 100 km altitude over the surface. It represented the ionosphere limit, although 100 km was not exactly the altitude of the ionosphere. Theoretically the Schumann frequencies on Martian environment is given by[19],

$$f_n = \frac{c}{2\pi R_M}\sqrt{n(n+1)\left(1-\frac{h}{R_M}\right)} \quad (13)$$

One of the important factor, which facilitates Schumann resonances on a planet is the existence of electrical discharges in the planetary resonant cavity, which can be considered as sources of the electromagnetic waves to excite the planetary cavity. The Schumann resonances in the Earth-ionosphere cavity are produced by the global lighting activity. Although there has been no report of orbiter or lander optical images of lightning-like discharges, the charge separation and lightning strokes are considered possible in the Martian dust storms (Farrell et al., 1999).Terrestrial dust devils are known to be electrically active (Farrell et al., 2004).Theoretical investigations (Farrell et al., 1999, 2006; Zhai et al., 2006) and experimental studies (Eden and Vonnegut, 1973) of dust grain electrification show that electrical discharges can be generated in Martian dust storms. The scale of the discharges produced by the dust storms on the Earth is much smaller than that produced by thunderstorms. Therefore dust storms make very little contribution to the Schumann resonances and always neglected in studies of Schumann resonances on the Earth [3].

SR are supposed to occur on Mars, although many properties of the Martian environment are still unknown. One of the most important problems in modelling SR on Mars is to estimate electrical properties of the Martian ground and their influence on ELF wave's propagation [20].

4. RESULT AND ANALYSIS

In this work, the results point out the importance of studying SR on Mars and the need for further research in propagation of ELF waves in the Martian environment[20].

To determine the magnetic field and the electric field, Software that has been used is MATLAB. Since a majority of the programming languages cannot handle none integer array indexes, equations (11) and (12) must be converted into MATLAB code and thus desired result is obtained. MATLAB is the high-level language and it provides an interactive environment for the users worldwide. The spectrum in figure 3.3 is of the magnetic field, where the X-axis represents the number of time steps and the Y-axis represents the magnetic field.

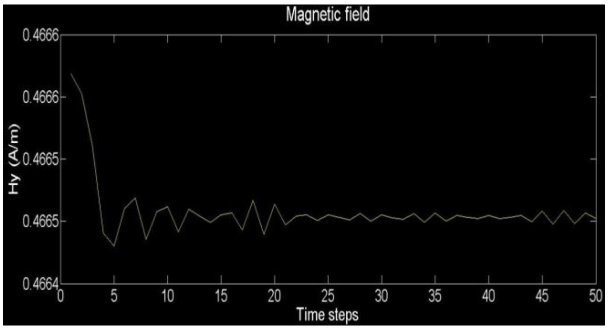

Figure 4.1 Result showing the magnetic field

The spectrum shown in the figure 3.4 is the plot of Electric field, where the X-axis represents the number of time steps and the Y-axis represents the electric field. The electric field will generate the magnetic field and the magnetic field will in turn generate the electric field. Thus, the magnetic and electric fields will help for obtaining the solutions of the problems that are robust.

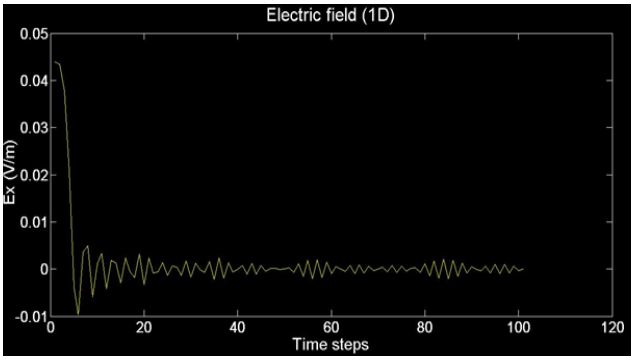

Figure 4.2 Result showing the electric field

SR Mode (Hz)	Observed	Model	f_n
f_1	9.6	8.8-14.3	9.6
f_2	19.2	16.1-25.8	19
f_3	27.8	23.6-37.4	30

Table 4.3 The Schumann Frequency mode values [22]

The final result of frequency spectrum gives the Schumann frequency. Here we have derived the Schumann frequency ranging from 25-26 Hz, whose theoretical value is 25.8. The Schumann frequency is obtained by using the Fast Fourier Transform method. Here, the Fast Fourier Transform (FFT) method is applied on the electric field (E_x)to obtain the frequency mode.

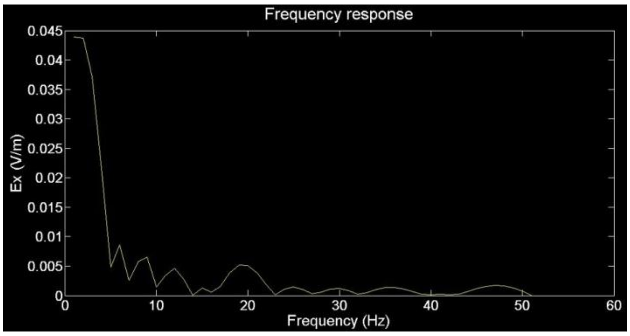

Figure 4.4 FFT of electric field showing Schumann frequencies

5. CONCLUSION

Natural electromagnetic waves may be generated near the surface of Mars due to electric discharges. The electric discharge could be due to the dust devil present in the cavity formed by the surface of Mars and the lower ionosphere of Mars. The electromagnetic waves trapped inside the cavity formed by the Mars and lower ionosphere can give rise to Schumann Resonance.

In this paper, we have implemented one dimensional finite difference time-domain technique to understand the Schumann resonance. The simulation results and analysis are given, which may be helpful to understand initially the possible lightning on the Mars. The electric charges could act as the source that generates the electric field, the electric field in turn will be converted in to the magnetic field and vice versa. The magnetic field will be further converted in to the electric field and thus the process continues. This conversion of the electric field and the magnetic field is termed as leap frog. The electric field contains the Schumann frequency modes which is realized when Fast Fourier Transform is applied on it.

Schumann frequency serves the base for determining lightning on the surface of Mars or any other planet. The electric and the magnetic field are implemented in the MATLAB software writing 1D code for the update equations of the electric field and the magnetic field. The Schuman frequency response can thus be obtained by performing Fast Fourier Transform (FFT).

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