Simplified Analytical Approach for an Airborne Bent Wire Ground Penetrating RADAR Antenna System

SUGANYA Jayaraman [1], James A. BASKARADAS [1], Umberto SCIACCA [2], Achille ZIRIZZOTTI [2]

[1] School of EEE, SASTRA Deemed to be University, Thanjavur, 613 401, Tamilnadu, India
[2] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

suganraj15@gmail.com, jamesbaskaradas@ece.sastra.edu, umberto.sciacca@ingv.it, achille.zirizzotti@ingv.it

Submitted July 7, 2020 / Accepted January 14, 2021

Abstract. *In this paper, modified analytical equations for the total electric field intensity in the far field region of a 10 MHz bent wire antenna have been proposed. The antenna system is meant for the airborne ground penetrating RADAR application for bedrock survey. This bent antenna is having vertical, slant and horizontal segments joined together along with the parasitic element. The current in the antenna wire is assumed to be a sinusoidal distribution which drops to zero at the ends. Current in both the energized and parasitic elements contribute to the fields in the far field region of the antenna system. Separate field equations for the various segments of the antenna system have been derived and finally summed to obtain the required equation for the electric field intensity at the far field region of the antenna. The MATLAB R2017b© simulation results of the far field antenna analytical equations show good agreement with the HFSS© simulation results of the 10 MHz antenna system. Direct measurements of these radiation characteristics in a typical GPR environment present a lot of practical difficulties. In this work, the influence of the helicopter on the 10 MHz GPR antenna during the airborne survey, is simulated using EMPro© and analyzed. This placement analysis resuls from the simulation gives us the appropriate range of distance values that can be maintained between the helicopter and antenna during the glaciological survey before performing the real time survey. A tradeoff between scattering parameter (S11) and directivity is considered to propose the optimum distance. The overall antenna structure seems to be a promising candidate for low frequency airborne GPR glacier explorations.*

Keywords

Analytical equations, bent wire antenna, electric field intensity, far field equations, placement analysis of GPR antenna, parasitic element

1. Introduction

For reducing the size and space occupied by the wire antenna, bending is introduced in the antenna wires. The importance and application of reduced size, wire antenna with good radiation efficiency are increasing more and more in all the fields. The better and the simplest way to reduce the size of lengthy wire antenna without losing the aerodynamical stability is to have inclined bends in the wire antenna. In the airborne ground penetrating RADAR (GPR) for temperate glacier surveys, reducing the size of the antenna to its maximum plays a vital role. The maximum reduced length 10 MHz antenna system is the requirement for the considered airborne glaciological bedrock survey.

Beneath the glacier ice surface, there will be air ice interfaces, snow ice interfaces, crevasses, lakes, water flowing streams, water, ice layer transitions, rock debris and bedrock. Deeper penetration into the different ice layers and a clear signature of the glacier bedrock detection are possible with the low frequency HF range of electromagnetic signals. Airborne Ground Penetrating RADAR antenna system will have both transmitting wire section and receiving wire section very close to each other, for transmitting the EM signals towards the glacier ice and receiving the echo signals from the subsurface, bedrock glacier regions. So, while deriving the radiated electric field equations in the far field regions of the whole antenna system, both transmitting and receiving antenna units combined electric field analysis should be done.

The far field analysis of any antenna system involves the investigation of the electric and magnetic field intensities in the far field zone. For the theoretical analysis, the derivation of field intensities are fundamental [1]. Analytical analysis of the bent wire using the derived general expression for the vector potentials, electric and magnetic field intensities have been reported in [2]. Current distribution of the various types of polygonal loop antennas has been analyzed in [3]. Theoretical formulation and the measurement of current distribution on the bent wires using the shielded loop have been investigated in [4]. In [5], the radiation characteristics of a thin wire V antenna has been discussed in detail using the travelling wave approach. The V antenna and the zig zag antenna are with inclined bent wires in its structure. The analytical analysis of these structures have also been reported in the literature.

The log periodic V dipole antenna is analyzed as V dipole in parallel connection [6] and its mutual coupling effects in [7].

For an infinite zig zag antenna [8], derivation for the approximate expression of the phase velocity along with the theoretical calculation for the radiation pattern and characteristic impedance are discussed. For a single zig zag antenna, radiation properties and approximate expressions for the radiation fields have been reported in [9]. Based on the radiated electric field by the elements of the yagi uda array, the far field analysis is done in [10]. The analytical field analysis of the yagi uda array uses the concept of parasitic elements. In the order to maximize the forward gain in the yagi uda array, the optimum spacing between the elements is essential and a method of repeated application of a perturbation procedure has been discussed in [11]. For short yagi aerials, the theoretical design data analysis has been discussed with different cases of driven and parasitic elements placement in [12].

For analyzing the bent wire antenna, we can consider the thin linear antenna as a reference for deriving the far field components. Eighty years of progress in thin linear antenna have been given in detail in [13]. Without analytical equations, some papers have been reported in the past discussing the bent wire concepts in various aspects. The effects on the rectangular spiral antenna have been analyzed for its varying wire radius [14] and arm bent with the help of input impedance calculation. The effects of feed wire on radiation characteristics are also discussed in [15]. The scattering and the radiation effects of the bent wire having junctions are analyzed in [16]. Prediction about the cross section of the bent wire is discussed in [17]. The field equations in the time domain and the characterization of the antenna is done in [18]. Pattern synthesis of wire antenna in a simplified method of analysis for linear array elements has been described in [19].

Analytical equations in the above mentioned papers are only for the active bent antenna which is not having the parasitic elements in their antenna system. For the yagi uda like structures, the driven, reflector, parasitic wires are straight without having the bents in them. In all the literature papers reported so far, HF 10 MHz GPR bent wire antenna having active, parasitic bent wires, with eight bent angles in its structure have not been analyzed analytically in terms of far field equations. In this work, a simplified analysis of the 10 MHz antenna system theoretically, in terms of far field equation has been discussed, which is the combination of linear wire elements, slant wire elements and parasitic wire elements. The 10 MHz bent wire antenna's [20] far field analytical equations for the electric field intensity are framed, simulated using MATLAB R2017b© and compared with the simulation results of the same antenna using HFSS© software. Plots of the calculated analytical result show good agreement with the simulation results obtained using the simulation software.

The antenna hanging below the helicopter [21], [22] will be influenced due to its interaction with the surrounding environment and can be a very challenging issue to solve. The complication will become worse when the HF antenna hanging below the helicopter is used for the survey of temperate glaciers. The structural stability of the HF wire antenna should be maintained throughout the airborne flying time. Predicting the performance and validating the procedure for an HF antenna below the helicopter is very difficult, acute with many difficulties.

The paper is organized as follows. The structure of the 10 MHz bent wire antenna [20] has been explained in Sec. 2. Analytical equations for the radiated fields from the various segments of the wire antenna have been discussed in Sec. 3. In that electric field equations for the vertical segments, slant segments and horizontal segments of the wire have been derived separately. And also combined equation for the electric field due to active wire elements, fields due to the parasitic wire elements of the GPR antenna in the far field are provided in subsections with the final analytical equation for the total electric field of the considered 10 MHz GPR antenna system have been discussed. In Sec. 4, with the help of simulation results, validation of the derived analytical equation using MATLAB R2017b has been done with the numerical results of the 10 MHz antenna system using HFSS software. Section 5 deals with the simulation results for the placement analysis of the 10 MHz GPR antenna system hanging below the helicopter. This is used to find out the optimum range of distances between the helicopter and the antenna system. Finally, Section 6 is provided with the conclusion of this research paper.

2. Structure of the Antenna

The basic structure considered for modification in this work is a thin wire dipole antenna. By altering the linear wire geometry, one can reduce or lower the resonant frequency of the whole antenna system, with acceptable tradeoffs on the fundamental antenna parameters which decides the performance of the antenna. Here, the conventional straight wire antenna is modified and bent to some angle for reducing the dimension of the antenna in its length significantly. The main disadvantage that should be compromised in the small size wire antennas are reduced gain, low radiation efficiency and bandwidth. The better way to reduce the dimension of the wire antenna is to introduce bends at appropriate lengths and angles for obtaining better radiation efficiency and other antenna parameters. From the literature discussed so far, meander, bowtie and zigzag type of wire antenna are found to be the better selection for the GPR application. But they cannot be used as it is, with their meander and zigzag shapes. The three main problems: radiation efficiency, bandwidth and impedance matching should be considered while reducing the size of the antenna. The bending concept used in those antenna can be utilized for forming new shapes and dimensions for the 10 MHz frequency of operation with both transmitting and receiving antennas. The newly framed antenna should resonate at the required frequency with reduced dimension and acceptable performance characteristics, when compared to the conventional straight dipole wire antenna.

The accurate characterization of the GPR antenna system can be made with the help of the far field analytical equations of the 10 MHz antenna. Analytical equations are developed for the 10 MHz bent wire antenna in this paper. Sinusoidal current distribution of the antenna structure with zero currents at the ends is assumed. The considered 10 MHz wire antenna consists of transmitting and receiving wire elements. The transmitting wire structure alone of the 10 MHz antenna system, can be decomposed into five segments which are joined together as shown in the figure. One vertical wire dipole, two (half) 45 degree slant wire dipole and two (half) horizontal dipole joined together with the structure shape specified as shown in Fig. 1 [20]. Symmetric segments are created in the receiving element as well. The receiving wire unit will act as the parasitic element to the transmitting wire unit and the whole structure will resonate at 10 MHz. Without the parasitic wire element, the transmitting wire elements will not act as an antenna for 10 MHz operating frequency. The total length of the transmitting wire is 16.4 m. In which, approximately 40% is the vertical wire segment, 20% is the slant wire dipole at each end of the vertical wire and 10% of the total length of the transmitting wire is the horizontal wire dipole, at each end of the slant wires. T1, T2 (T1 = T2 = 3.25 m), T3, T4 (T3 = T4 = 3.25 m), T5 & T6 (T5 = T6 = 1.7 m) are the six active segments in the transmitting wire unit. The antenna wire thickness in terms of radius is 0.0025 m and H = 2.3 m. The distance of separation between the Tx and Rx units is D = 0.6 m. The bent angle α is 45°. Same length and shape, as similar to that of transmitting segments, are there in the receiving wire unit which will act as the parasitic elements during the transmission time of the GPR antenna system. The radius of the considered wire is very thin when compared to the overall length and the wavelength of the antenna unit. The 10 MHz bent wire antenna structure [20] is as shown in Fig. 1. The change in the shape of the linear wire antenna will have its influence in the impedance of the antenna and the radiation characteristics of the antenna system.

The inclusion of the two side bents in the linear active element and the presence of the identical parasitic element, make the whole antenna system to resonate at 10 MHz frequency with the acceptable values of the antenna parameters in the far field region. 6.5 m linear wire with the Tx and Rx will not act as an antenna for 10 MHz, since the reflection coefficient and the VSWR is very high. This bad S11 and VSWR values can be corrected by introducing one bend at the ends of the linear existing wire at a slant angle of 45 degrees. The expected 10 MHz resonant frequency will be obtained after introducing the second bend at the ends of the first bend. The peak gain value with the 6.5 m Tx linear element alone is 1.63. This decreases to 1.51 peak gain value after the inclusion of Rx and first bent on either side of the linear element. Then the peak gain value

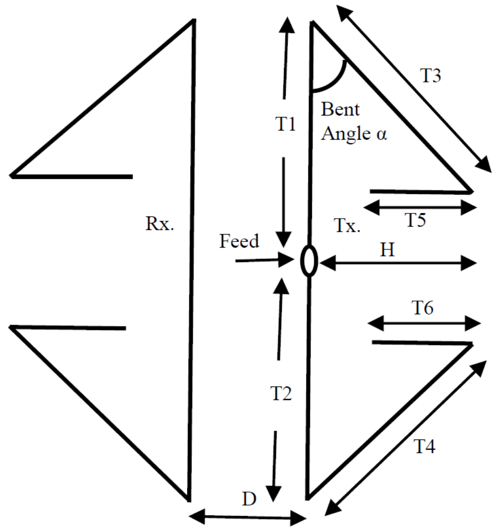

Fig. 1. 10 MHz bent wire GPR antenna [20].

is 1.6 for 10 MHz structure with the second bent at the ends of the first bent.

The antenna is designed using the copper wire. During the transmission, due to the fields around the driven transmitting wire unit, the current is induced in the receiving parasitic element also. The 10 MHz bent wire dipole system is energized using a balanced transmission line. Radiation from the transmission line is assumed to be zero here. The surrounding medium of the antenna system is air here, as the antenna system is going to hang below the helicopter. Method of analysis of the 10 MHz antenna is same as that of the thin linear antenna. Current distribution in both the transmitting and receiving (parasitic element during transmission) wire units will have its influence in the far field region at point "P". The current in the horizontal and in the slant segments are not getting vanished. The radiation pattern of the 10 MHz antenna is similar to that of the normal dipole wire antenna.

This 10 MHz antenna system is having the linear and bent elements in both the driven and the parasitic elements and also the whole system performance is not getting degraded due to the presence of the parasitic element. The change in the self-impedance and mutual impedance of the antenna system depends on the total length of the wire elements, type of the antenna material used, inclined angle of the bent wire elements, distance of separation of the wire segments and excitation feed type. Shift in the resonant frequency and severe problems will be there for any antenna system placed in the real working environment. This is due to the interaction of the antenna system with its surroundings with several unknown electrical, mechanical properties.

GPR is the contactless method used to identify the target using the antenna system in the glacier study. Antenna plays the very important role which determines the frequency of operation of the system and is the one which is having the direct interaction with the real environment. GPR antennas are more unique and different from the normal antennas, due to the application specific operating conditions. The needed features, performance specifications, properties for the GPR system are required before designing the optimized antenna geometry for a specific application. GPR configurations for different applications enforce different constraints on antenna type and design to achieve high performance antennas as a result to obtain the clear subsurface image. The physical size of the antenna and the gain values are dependent quantity of the working frequency. There should be some proper compromise in the quantities such as gain, size and frequency of the antenna to achieve the GPR system compactness. The ultimate consideration while designing the GPR antenna system is to have both transmitting and receiving elements within it and with lower side lobes. This is helpful to avoid the power loss in the unwanted cross track direction during the survey time of the temperate glacier ice.

Depending upon the measurement area conditions and the needed penetration depth in that specified survey area, the GPR operating frequency band may range from few MHz to a few GHz. The primary application of the low frequency - HF range (3 to 30 MHz) ground penetrating RADAR is to image the buried bedrock topography of the temperate glaciers. Narrow pulses will be used by the high frequency GPR for obtaining better resolution without deeper penetration. For deeper penetration, low frequency GPR systems are in need. The attenuation of the high frequency EM signal increases with the increase in the penetration depth. So the high frequency signals are not able to penetrate much deeper into the surface layers for identifying target such as bedrock. In this situation, we are in need of a low frequency GPR system.

Airborne survey, especially, helicopter borne GPR survey will be more helpful to collect complex data safely and rapidly from large potentially high risk areas. An airborne survey can cover wider area, but deeper penetration is limited when compared to the ground based system. Integrating the antenna system with the aircraft or helicopter in an airborne system is a very important aspect to be considered seriously for doing the survey effectively. The suitable antenna frequency, relative positioning, placement, orientation of the transmitting, receiving GPR antennas and appropriate transmitter power are vital, critical parameters for mapping the complex glacier bedrock. The weight of the antenna used for the airborne system should be reduced as much as possible. The weight of the antenna is the dependent quantity of its size. The size of the antenna is determined by the operating frequency of the GPR system.

Existing temperate glacial survey area have difficulties and issues such as the varying electrical properties of the dispersive, lossy, inhomogeneous, no-linear, anisotropic dielectric materials within the complex geometry glacial layers, irregular surface and subsurface, impose a difficult job in the modelling of the GPR antenna system. Because of the presence of the combination of layers of ice, water, debris, rock, large sized stones, englacial channels in the temperate glacier regions, the GPR survey needs low frequency system setup. Melt water in voids, cavities and pockets in very less to large dimension levels may cause the high frequency radar signal to scatter internally within the ice layers and leads to the loss of signal sometimes. The internal scattering effects during the investigation of the temperate glacier regions are greatly reduced with the usage of low frequency GPR systems at frequencies below about 10 MHz.

3. Radiated Fields from the Segments of the Wire Antenna

In the analysis of the radiation from the considered bent wire antenna system, first we have to specify the current in the active and parasitic source wire segments, then the fields radiated by each segments. Electric and magnetic vector potentials are the auxiliary functions which are used as a mathematical tool for the analysis purpose to obtain the electric field intensity E and magnetic field intensity H in the far field region of the considered antenna. The (x,y,z) represents the observation point coordinates and (x',y',z') represents the source point coordinates. The whole evaluation of the existing fields in the far field region of the antenna system depends on the most important actual current distribution quantity along each wire segments. The current in the Tx and Rx segments are sinusoidal in nature with the maximum current value at the feeding position and zero value of current at the ends of the wire segments. The antenna system is placed in the air medium. I_0 is the maximum amplitude of the assumed sinusoidal current distribution.

3.1 Tx Vertical Segments

T1, T2 are the vertical segments, oriented parallel to the Z axis of the coordinate system. In that, each vertical and horizontal wires can be assumed as the vertically and horizontally placed linear antenna elements respectively. 'r' is the distance from the origin of the coordinate system to the observation point 'P' in the far field region of the antenna system. 'R' is the distance between the considered antenna wire segments to the observation point under consideration. $k = \omega\sqrt{\mu_0\varepsilon_0}$ is the free space wave number. In that, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the permittivity of free space. The overall length of the antenna for the transmitting section is designated as 'T'. I_{vertical} is the needed current distribution in the vertical segment of the considered antenna and is given by

$$I_{\text{vertical}}(x'=0;\, y'=0;\, z') = \begin{cases} \hat{a}_z I_0 \sin\left(k\left(\dfrac{T}{2}-z'\right)\right); & 0 \le z' \le \left(\dfrac{T}{5}\right) \\ \hat{a}_z I_0 \sin\left(k\left(\dfrac{T}{2}+z'\right)\right); & \left(\dfrac{-T}{5}\right) \le z' \le 0 \end{cases} \quad (1)$$

The finite length vertical wire antenna is subdivided into number of small infinitesimal dipoles of length $\Delta z'$. $\hat{a}_z$ is the unit vector in Z axis direction. For such an infinitesimal dipole, the far field electric field component is given by

$$\mathrm{d}E_{\theta(\text{vertical})} \simeq \frac{\mathrm{j}\eta k I_{\text{vertical}}(x',y',z')\,\mathrm{e}^{-\mathrm{j}kR}}{4\pi R}\sin\theta\,\mathrm{d}z'. \quad (2)$$

η is the intrinsic impedance of the air medium and is equal to 120π.

For obtaining the far electric field intensity due to the whole vertical segment of length $2T/5$, we have to integrate $\mathrm{d}E_\theta$ with respect to the length along with the application of far field approximations

$$E_{\theta(\text{vertical})} \simeq \frac{\mathrm{j}\eta I_0 k\,\mathrm{e}^{-\mathrm{j}kr}\sin\theta}{4\pi r}\left\{\begin{array}{l}\displaystyle\int_{\frac{-T}{5}}^{0}\sin\left(k\left(\frac{T}{2}+z'\right)\right)\mathrm{e}^{\mathrm{j}kz'\cos\theta}\,\mathrm{d}z'+\\ \displaystyle\int_{0}^{\frac{T}{5}}\sin\left(k\left(\frac{T}{2}-z'\right)\right)\mathrm{e}^{\mathrm{j}kz'\cos\theta}\,\mathrm{d}z'\end{array}\right\}. \quad (3)$$

Integrating the current on the vertical segment with respect to z' and applying limits which is confined only to the vertical segment length will yields the $E_{\theta(\text{vertical})}$ and is given by

$$E_{\theta(\text{vertical})} \simeq \frac{\mathrm{j}\eta I_0\mathrm{e}^{-\mathrm{j}kr}}{2\pi r\sin\theta}\left[\begin{array}{l}-\cos\left(\frac{kT}{2}\right)-\\ \cos\theta\sin\left(\frac{3T}{10}\right)\sin\left(k\left(\frac{T}{5}\right)\cos\theta\right)+\\ \cos\left(\frac{3T}{10}\right)\cos\left(k\left(\frac{T}{5}\right)\cos\theta\right)\end{array}\right]. \quad (4)$$

3.2 Tx Slant Segments

The slant wire segments can also be considered as the antenna elements away from the origin which is inclined with an angle with respect to the reference axis. T3, T4 are the slant wire segments which are inclined to 45° angle with respect to the Z axis. I_{slant} is the current in the slant segment of the transmitting antenna system. Here the term $\cos\alpha$ has been included in the considered sinusoidal current equation. Since the segment is forming an angle of $\alpha = 45°$ with the Z axis. The current is confined to the wire segments. So the direction of the current is same as that of the orientation of the segments in the coordinate axis. The slant segment current distribution is given by the following equation

$$I_{\text{slant}}(x'=0;\ y'=0;\ z') = \left\{\begin{array}{l}\hat{a}_z\,\frac{I_0}{\cos\alpha}\sin\left(k\left(\frac{T}{2}-z'\right)\right);\ \left(\frac{T}{5}\right)\le z'\le\left(\frac{2T}{5}\right)\\ \hat{a}_z\,\frac{I_0}{\cos\alpha}\sin\left(k\left(\frac{T}{2}+z'\right)\right);\ \left(\frac{-2T}{5}\right)\le z'\le\left(\frac{-T}{5}\right)\end{array}\right. \quad (5)$$

The finite length slant wire antenna is subdivided into number small infinitesimal dipoles of length $\Delta z'$. For such a slant infinitesimal dipole inclined at an angle of 45° to the Z axis, the far field electric field component is given by

$$\mathrm{d}E_{\theta(\text{slant})} \simeq \frac{\mathrm{j}\eta k I_{\text{slant}}(x',y',z')\,\mathrm{e}^{-\mathrm{j}kR}}{4\pi R\,\cos\alpha}\sin\theta\,\mathrm{d}z'. \quad (6)$$

Integrating the I_{slant} on the slant segment with respect to z' and applying limits which is confined only to the total slant segment length will gives the $E_{\theta(\text{slant})}$

$$E_{\theta(\text{slant})} \simeq \frac{\mathrm{j}\eta I_0 k\,\mathrm{e}^{-\mathrm{j}kr}\sin\theta}{4\pi r\cos\alpha}\left\{\begin{array}{l}\displaystyle\int_{\frac{-2T}{5}}^{\frac{-T}{5}}\sin\left(k\left(\frac{T}{2}+z'\right)\right)\mathrm{e}^{\mathrm{j}kz'\cos\theta}\,\mathrm{d}z'+\\ \displaystyle\int_{\frac{T}{5}}^{\frac{2T}{5}}\sin\left(k\left(\frac{T}{2}-z'\right)\right)\mathrm{e}^{\mathrm{j}kz'\cos\theta}\,\mathrm{d}z'\end{array}\right\}. \quad (7)$$

After integrating and applying the limit which corresponds to the slant wire length will gives the $E_{\theta(\text{slant})}$ and is given by

$$E_{\theta(\text{slant})} \simeq \frac{\mathrm{j}\eta I_0\,\mathrm{e}^{-\mathrm{j}kr}}{2\pi r\,\sin\theta\,\cos\alpha}\left[\begin{array}{l}\cos\theta\sin\left(\frac{3kT}{10}\right)\sin\left(k\cos\theta\left(\frac{T}{5}\right)\right)-\\ \cos\left(\frac{3kT}{10}\right)\cos\left(k\cos\theta\left(\frac{T}{5}\right)\right)-\\ \cos\theta\sin\left(\frac{kT}{10}\right)\sin\left(k\cos\theta\left(\frac{2T}{5}\right)\right)+\\ \cos\left(\frac{kT}{10}\right)\cos\left(k\cos\left(\frac{2T}{5}\right)\right)\end{array}\right]. \quad (8)$$

The current continuity from the antenna wire feed position to the end of the wire is considered in the derivation which leads to the increase in the number of cosine and sine terms in the derived equations. Bending the simple structure, linear half wavelength wire dipole antenna to some angle is one of the approaches used for reducing the space occupied by the straight line wire antenna. The length of the antenna and the size of the antenna is reduced by introducing various bents in the linear wire. Here in the 10 MHz wire antenna, such inclined bents are achieved with the slant segments placements at the ends of the linear wire elements on either side.

3.3 Tx Horizontal Segments

T5, T6 are the horizontal wire segments, placed parallel to the Y axis. The current value becomes zero at the ends of the horizontal segment. The below given current equation (9) is for the one horizontal segment T5 for its total length $T/10$,

$$I_{\text{horizontal1}}(x'=0;\ y';\ z'=0) = \hat{a}_y\,I_0\sin\left(k\left(\frac{T}{2}-y'\right)\right);\ \left(\frac{2T}{5}\right)\le y'\le\left(\frac{T}{2}\right). \quad (9)$$

The finite length horizontal wire antenna is subdivided into number of small infinitesimal dipoles of length $\Delta y'$. $\hat{a}_y$ is the unit vector in Y axis direction. For such an infinitesimal dipole which is parallel to the Y axis and placed in the YZ plane, the far field electric field component is given by

$$\mathrm{d}E_{\theta(\text{horizontal1})} \simeq \frac{-\mathrm{j}\eta k I_{\text{horizontal1}}(x',y',z')\,\mathrm{e}^{-\mathrm{j}kR}}{4\pi R}\cos\theta\sin\phi\,\mathrm{d}y'. \quad (10)$$

Integrating the $I_{\text{horizontal1}}$ on the horizontal segment with respect to y' and applying limits which is confined only to the segment length will gives the $E_{\theta(\text{horizontal1})}$

$$E_{\theta(\text{horizontal1})} \simeq \frac{-\mathrm{j}\eta I_0 k\,\mathrm{e}^{-\mathrm{j}kr}\cos\theta\sin\phi}{4\pi r}\left\{\int_{\frac{2T}{5}}^{\frac{T}{2}}\sin\left(k\left(\frac{T}{2}-y'\right)\right)\,\mathrm{e}^{\mathrm{j}ky'\cos\theta}\,\mathrm{d}y'\right\}. \quad (11)$$

After integrating the current with respect to its length and applying the limit which corresponds to the horizontal wire length will yield the $E_{\theta(\text{horizontal1})}$ and is given by

$$E_{\theta(\text{horizontal1})} \simeq \frac{-\mathrm{j}\eta I_0\,\mathrm{e}^{-\mathrm{j}kr}\cos\theta\sin\phi}{4\pi r} \cdot \left\{\left[\frac{\mathrm{e}^{\mathrm{j}k\frac{T}{2}\cos\theta}}{\sin^2\theta}\right] - \left[\left(\frac{\mathrm{e}^{\mathrm{j}k\frac{2T}{5}\cos\theta}}{\sin^2\theta}\right)\left(\mathrm{j}\cos\theta\sin\left(\frac{kT}{10}\right)+\cos\left(\frac{kT}{10}\right)\right)\right]\right\}. \quad (12)$$

The above given equation is only for one Tx horizontal segment. So, for the another horizontal segment, same equation can be used as $E_{\theta(\text{horizontal2})}$, since the placement of the T5, T6 segments is in the side of positive Y axis and integrating length limits for both the horizontal segments are same.

3.4 Fields due to the Active Wire Elements

All the vertical, slant and horizontal wire segments of the transmitting and receiving units of the 10 MHz bent wire antenna are at equal distance from the ground. Because the bents are done laterally to the wire segments, all the segments are in the same YZ plane. And also same side lateral bending at both the ends of the transmitting wire antenna and also for the receiving wire antenna. The total $E_{\theta(\text{active})}$ (13) is the summation of the all the field which we have derived individually for the segments and is given below,

$$E_{\theta(\text{active})} \simeq E_{\theta(\text{vertical})} + E_{\theta(\text{slant})} + E_{\theta(\text{horizontal1})} + E_{\theta(\text{horizontal2})}. \quad (13)$$

The 10 MHz antenna should be placed below the helicopter for glacier bedrock survey. When compared to the conventional wire dipole system, this 10 MHz antenna size is lesser. In order to reduce, limit the space occupied by the 10 MHz antenna and to maintain the constant height of the whole system from the ground glacier surface, bending the wire antenna laterally is done. The largest dimension of this bent wire 10 MHz antenna is lesser than the length of the conventional λ/2 dipole antenna. Bent wire 10 MHz dipole antenna is shorter than the straight wire dipole antenna used for the glaciological survey.

If the length of the wire antenna increases, the inductance increases. Bending the linear wire will lead to the increase in the mutual capacitance between the adjacent segments of the whole antenna system also. Here, the bending is done laterally which increases the area occupied by the antenna system. Due to bending, there will be consistence in the decrement of the resonant frequency of the wire with some variation in the inductance and capacitive effects.

3.5 Fields due to the Parasitic Wire Elements

While dealing with reduced size antenna system, the mutual coupling effects will appear as an issue, which affects and degrades the actual working performance characteristics of the antenna. In this 10 MHz antenna system, both transmitter and receiver wire units will be there. The distance of separation between them may not be half wavelength here. Why because, the wavelength for the 10 MHz frequency is 30 m. Half of the wavelength value will be 15 m. We are unable to place the transmitter 15 m apart from the receiver antenna. So, we have to go for the very minimal distance between them. In this situation, the contribution of the receiving segments as a parasitic elements, to the transmitting units will be there, due to strong mutual coupling between them. As a whole, the antenna system has to resonate at 10 MHz frequency.

The distribution of current along the parasitic element is similar to that of the current distribution in the active element. Since both the shape of the active Tx and parasitic Rx are same. Due to this, the individual segments will have its equal field composition in the far field region. During the transmission of EM signal, even though we are providing feed only to Tx section of the antenna system, due to the mutual coupling of fields in between the driven bent elements and the parasitic structure, there will be current flow in the parasitic element also. The electric field radiated by each segments of the antenna system are combined together to produce the total field in the far field region of the 10 MHz antenna system.

In the GPR antenna system, both the Tx and the Rx section wire should be there for transmitting the EM waves through the Tx wires into the ice and receiving the reflected echoes with the help of the Rx wires. During the transmission mode, the Rx will act as the parasitic element for the driven active Tx wire and during the receiving mode the Tx bent wires will act as the parasitic element for the receiving wire units. Both the wire sections are separated by 0.6 m. Due to the mutual impedance in between the driven and Rx bent wires, the current is induced in the parasitic wire also. Since these two antenna wires are near to each other, some energy is getting coupled to the passive wire from the active wire. The amount of energy getting coupled to the parasitic element will depend on the current distribution on the active wire element, radiation characteristics of the bent wires, separation of the Tx from the Rx and the orientation of the various segment of wires in the antenna system. There is a significant contribution of the parasitic wire segments to the driven wire segments, for resonating the whole antenna system at 10 MHz. Without the Rx wire segments, the Tx wire segments alone will not resonate at 10 MHz. The available power energy in the far field region of the GPR antenna system depends not only on the excited section but also the coupled excitation in the parasitic element. So, in the performance of the GPR antenna system, the parasitic element plays an important role.

The simplest way to find out the optimum distance between the elements is to increase the separation distance from the minimum to the maximum acceptable range of values. Through numerical simulation results, it has been confirmed that for the optimum separation of 0.6 m, the antenna system parameters like return loss, VSWR, peak gain, Z parameter and the radiation efficiency are in the acceptable values. The degradation of the antenna system performance in terms of resonating frequency and the antenna parameters in the far field region should be kept in mind while finding out the optimum distance between the active and passive element spacing. The optimum spacing in between the Tx and Rx wires in this GPR antenna system is considered to be as 0.6 m, in order to operate the whole resonant system at 10 MHz.

Due to the 0.6 m separation between the active and the parasitic element of the antenna system, which is considered to be as minimum, when compared to the total length of the antenna, we can assume the maximum current in the parasitic wire also as I_0. Substituting in the active element E field equation will give us the field due to the parasitic element in the far field region of the antenna system. So, at the far field point ‘P’, the electric field intensity $E_{\theta(\text{parasitic})}$ due to the parasitic element is given by

$$E_{\theta(\text{parasitic})} \simeq \left(E_{\theta(\text{active})}\right). \tag{14}$$

3.6 Total Electric Field (Tx & Rx)

The total field of the GPR antenna system is the summation of the fields from the individual linear horizontal, vertical and slant antenna segments of the active and parasitic wires. The radiation properties of the horizontal, vertical and slanting wire are examined separately and summed together at the last. The E_r and $E_\emptyset$ are approximately equal to zero in the far field of the antenna system. The approximate $E_{\theta(\text{Total})}$ - total electric field is the summation of field due to the active segments and the parasitic segments and is given by

$$E_{\theta(\text{Total})} \simeq E_{\theta(\text{active})} + E_{\theta(\text{parasitic})}. \tag{15}$$

The total magnetic field intensity of the far field component $H_{\emptyset(\text{Total})}$ can be calculated using the following formula

$$H_{\phi(Total)} \simeq \frac{E_{\theta(Total)}}{\eta}. \tag{16}$$

The radiation efficiency decreases as the number of bends increases in the active and parasitic element of the antenna system. Modification in the dipole or monopole wire antenna will changes its physical and electrical characteristics to a greater extent. If the physical antenna size, shape are varied other than the linear structure the corresponding changes in the impedance happen in the antenna system which will drastically change the antenna characteristics. Reduction in the physical size of the antenna will reduce the antenna bandwidth to the greater extent.

4. Simulation Results

Plotting of the derived $E_{\theta(\text{Total})}$ analytical equation for the 10 MHz bent wire GPR antenna system using MATLAB R2017b is as shown in Fig. 2. If we consider the 10 MHz antenna as a single straight wire, the total length of the single wire will be 15 m. But in the case of ground penetrating RADAR system, we are in need of two separate antenna (one antenna for transmitting the electromagnetic signal and another one antenna for receiving the reflected echo from the glaciers). Both the antenna should be placed close to each other with more or less same radiation characteristics and should be operated at the same frequency but at different timings. If two straight wires of 15 m are used in which both the wires are separated by some distance they will act as a bad radiator rather than the good radiating antenna system.

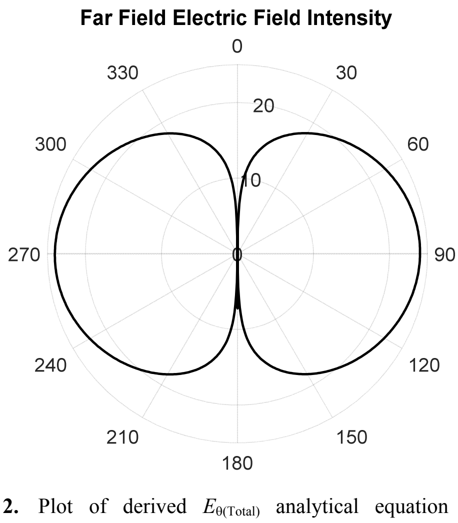

Fig. 2. Plot of derived $E_{\theta(\text{Total})}$ analytical equation using MATLAB.

The antennas will be at the same location and hence it will create mutual coupling among themselves. This will consequently change, disturb the operating frequency and antenna parameters values. So considering all these issues in mind, this bent antenna is designed in the better way, to operate at 10 MHz, as a whole system with eight bent angles, including the transmitting & the receiving antenna units with vertical, slant and horizontal segments in it. So now, it is easy for us to analyze the radiated fields separately for various segments of the antenna system and finally add together to obtain needed analytical electric field equation at the far field.

The HFSS numerically simulated total electric field intensity result of the 10 MHz bent wire antenna is given in Fig. 3. The current flow is getting continued at the bents of the antenna structure, but it is not having zero value at the end of the vertical and also at the end of the slant segments. The current is getting vanished and become zero, only at the end tip of the horizontal segments. This is the reason that the analytical equation for the far field electric field intensity is having many terms when compared to the normal linear antenna.

We have considered here that the radiation from the feed wire is having the minimum effect in the total radiated field from the antenna system. The antenna is fed with the uniform transmission line which is having the constant real characteristic impedance. The current distribution in the feed wire is not having much contribution to the field radiation by the antenna system is assumed here. With this we have examined thoroughly only about the antenna system. Because of the presence of the gap at the feed point of the antenna, there will be capacitance effect. The gap is fixed, small and hence the capacitance effect is almost constant and negligible.

In the paper, first, the electric field equation for the 10 MHz bent wire antenna is derived (analytical way of finding the far electric field values) and the derived final far electric field equation are simulated using MATLAB R2017b software. The structure is having the vertical, slant and the horizontal segments in the active and parasitic wire

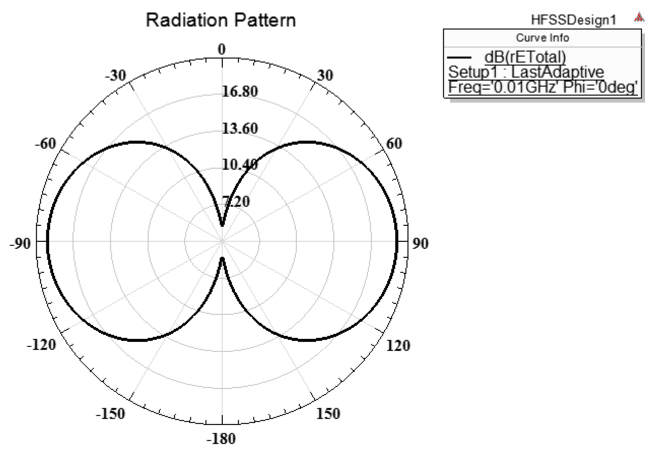

Fig. 3. Plot of total electric field of the 10 MHz bent wire antenna using HFSS.

structures. Second, for the same bent wire antenna structure resonating at 10 MHz, the far electric field is plotted using the HFSS (Finite Element Method) software (numerical method for finding the field values). % Error = [(Analytical value – Numerical value)/Analytical value]× 100. The estimated error between the analytical result (Equation - MATLAB R2017b) and the numerical result (HFSS) is 26.4%. The analytical mathematical simulation result values are considered as reference for calculating the estimated error. While deriving the analytical equation, we have considered the maximum current in the vertical, slant and horizontal segments are the same as I_0. This is not the actual situation prevailing in the bent antenna. The current is maximum at the feed position and later on it starts decreasing towards its ends. That is, the maximum amplitude of the current will be maximum in the vertical segment and goes on decreasing in the slant and vertical segment. Because of that assumption there may be increase in the magnitude value of the electric field plotted using the equation when compared to the numerical results and the estimated error value will be 26.4%.

Our interest in this paper is to obtain the far field - electric field intensity for the specified bent antenna structure using both analytical and numerical analysis methods. Due to the antenna structure complexity, only a few number of practical antennas have been examined analytically. It will be more effective to solve the electromagnetic field oriented problem of a wire antenna using analytical & numerical methods and proving the solutions in both the approaches are almost same. We tried in obtaining the far field solutions using both the methods. The total electric field of the 10 MHz bent wire antenna has been obtained using the HFSS (frequency domain solver) software which are the numerical results. In HFSS, the electromagnetic fields around the antenna structure are solved using the finite element method. The 10 MHz whole antenna structure is divided into small volumes approximate meshes and the electric field is solved for the entire structure volume. In the meshes the Maxwell's equations are solved. Automatic adaptive meshing is the most important part in the HFSS. With the help of the adaptive refinement process, the initial mesh created by the HFSS is refined. This process is continued till the result is converged and accurate. Normally numerical solutions are mostly valid for the specified mentioned frequency sweep and it follows the trial and error procedures to obtain the approximate solutions. But it handles the complex structure geometry shape very efficiently by forming the volume based mesh to find out the field solutions. Numerical method of analysis will provide an approximate solution whereas the analytical method of analysis will yield the exact solution results for the problem under consideration. The results we have obtained using the MATLAB software is the simulation of the analytical results (derived equation). Analytical theories are more general, common approach and clear to understand. Analytical solutions deal with the problem in the well understood way of approach and are used to yield the exact solutions using the standard framed procedures. The mathematical assumptions, rules of a wire antenna problem can be clearly understood in the analytical way of explaining the field solutions. In terms of accuracy, analytical solutions are better than the numerical solutions. Finding a solution for the wire antenna related electromagnetic field problems in both analytical and simulation ways of analysing methods will be stronger and acceptable.

In the analytical way of analysing the far electric field of the 10 MHz bent wire antenna, the current distribution of the antenna is specified first and then standard analysing procedure is used to analyse the 10 MHz bent wire antenna. If the diameter of the wire is less than 0.05λ, we can assume the current distribution of the wire antenna as sinusoidal. As the frequency of operation of this antenna structure is 10 MHz, the corresponding wavelength value is 30 meters. The 0.05λ is 1.5 meters for the 10 MHz frequency. But in our bent antenna design, the diameter of the 10 MHz bent antenna wire is 5 mm which is less than the 0.05λ value. So in the analytical way of analysing the antenna structure, the current distribution is considered to be as sinusoidal. Using the intermediate auxiliary vector potentials, the field intensities are derived in the analytical approach for finding the field equations of the wire antenna. The magnetic vector potential (A) and the electric vector potential (E) are the auxiliary functions which are found to be the important mathematical tools used to derive the field intensity of an antenna in the far field region. The electric and magnetic field intensities are the physically measurable quantities for an antenna. The two step procedure is followed (traditional way of solving wire antenna). First, the vector potentials are found out using the integration relations with the sources current densities J (electric current source) and M (magnetic current source). Secondly, the field intensities E, H are derived using the differentiation of A and F. Proving the 10 MHz antenna structure using the analytical equations can be contributed as an added valid proof for the numerical results. Since the 10 MHz wire antenna structure is in bent shape and having active and parasitic elements within it, the analytical solution for the far fields of this structure are not having simple and less number of terms. Complex integration and the increased number of terms in the derived far field mathematical expression limits us to do the further derivation expression for the power values, gain, and directivity.

5. Placement Analysis

The 10 MHz bent wire antenna considered in this work has to be tested for its performance to find out the optimum distance between the helicopter and the antenna in the actual field to be surveyed before going for the final deployment survey. In principle, the whole antenna should be fabricated and tested in the field. Then appropriate modifications are made in the distance between the helicopter and the antenna for improving and optimizing the performance of the antenna system for the measurement site. The whole process is time consuming and expensive one. Considering the practical difficulties (both logistics and technical) in testing a low frequency airborne ground penetrating radar antenna in the field, for optimizing the distance between the helicopter and antenna, the placement issue has been simulated using a numerical analysis tool that gives very good approximation which will be close to field experiment results. Here, the influence of the helicopter on the 10 MHz bent wire antenna is studied using the EMPro© software. An optimized distance between the helicopter and the antenna system is determined which will be then used for field measurements.

Figure 4 represents the scattering parameter (S11) and 2D radiation pattern of the 10 MHz bent wire antenna (without helicopter) simulated using EMPro©.

Figure 5 shows the arrangement of the helicopter and the antenna during an airborne survey, which will be very close to real time GPR survey. The helicopter considered here is Eurocopter AS350 (CAD model from https://grabcad.com/library/tag/helicopter) with the exact dimension. This is the model of the helicopter that is used by most of the GPR survey teams in Antarctica. The material of the helicopter is considered to be a generic conductor/fiber as our interest is only to study the effect of the helicopter on the electromagnetic waves radiated from the antenna system.

The S11 value versus frequency for the various distance between the helicopter and the 10 MHz antenna system have been plotted in Fig. 6. The distance (d) in between the helicopter and the antenna is varied from 2 m to 10 m and results have been plotted.

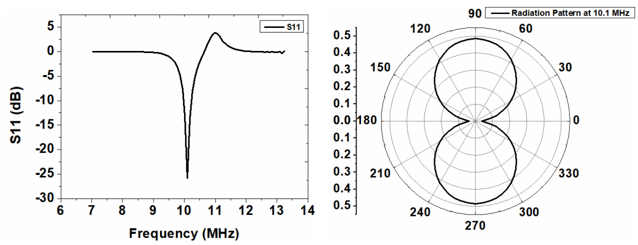

Fig. 4. S11 & 2D pattern of the 10 MHz antenna system (without helicopter) in free space.

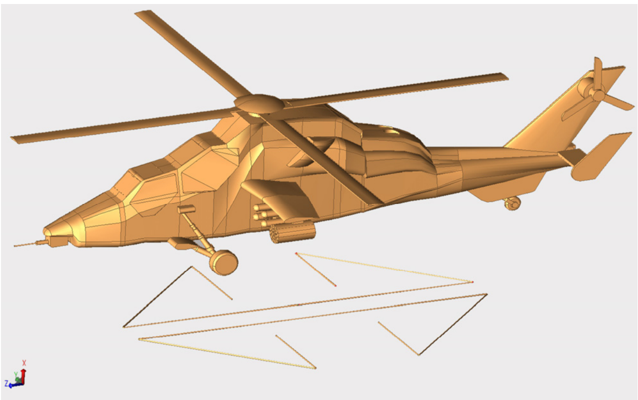

Fig. 5. Placement of the antenna below the helicopter.

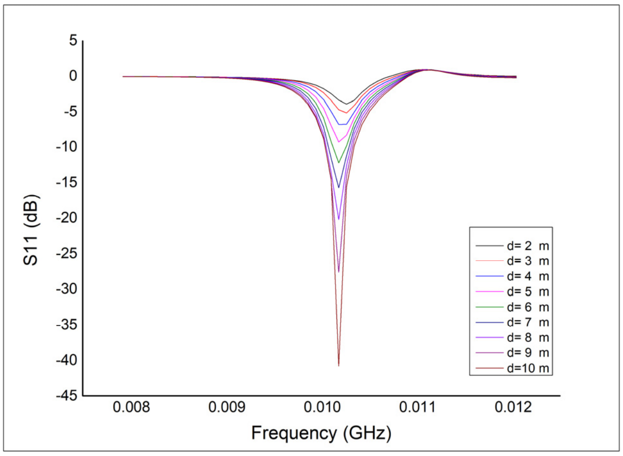

Fig. 6. S11 vs. frequency for various distance between the helicopter and the antenna.

Distance *d* [m]	Frequency [MHz]	S11 [dB]
1	10.2	–3.9
2	10.2	–5.1
3	10.1	–6.7
4	10.1	–9.2
5	10.1	–12.2
6	10.1	–15.6
7	10.1	–20.2
8	10.1	–27.6
9	10.1	–40.7
10	10.1	–26.1
11	10.1	–21.3
12	10.2	–22.6
13	10.2	–27.5
14	10.2	–40.2

Tab. 1. S11 vs frequency with varying helicopter-antenna distance.

Table 1 lists the value of S11 at the resonant frequency of the antenna system along with the helicopter for various helicopter antenna distances from 1 m to 14 m. From 1 m to 4 m distance of separation, the S11 values are greater than –10 dB which are not suggested for a good radiating system. The influence of the helicopter on the radiation of the hanging antenna is more at these distances. So these distances are not recommended for the real time survey. Starting from the distance 5 m and greater than that, the S11 is less than –10 dB which are the suitable range of values. The antenna resonant frequency does not vary that much from the required 10 MHz value. Lesser value of S11 (–40.7 dB) is obtained at $d = 9$ m.

The 2D radiation pattern of the E field with varying helicopter-antenna distance is given in Fig. 7. From these radiation patterns, it is evident that up to the distance of $d = 4$ m, the influence of the helicopter is more. The proximity of the helicopter short-circuits the antenna, so the radiation pattern cannot be so reliable which is well observed with very poor S11 values. But the antenna pattern seems to be prominent above the helicopter. This can be due to the focusing effect of the diffracted radiowaves from the irregular edges of the helicopter shape. If the helicopter is considerd or modelled to be a flat conductor, then it should reflect all the radiowaves from the antenna and would act like a yagi reflector at a proper distance. So, flat conductor modeling of the helicopter is not appropriate. Above $d = 4$ m, the effect of the helicopter starts reducing and is evident from the 2D radiation patterns.

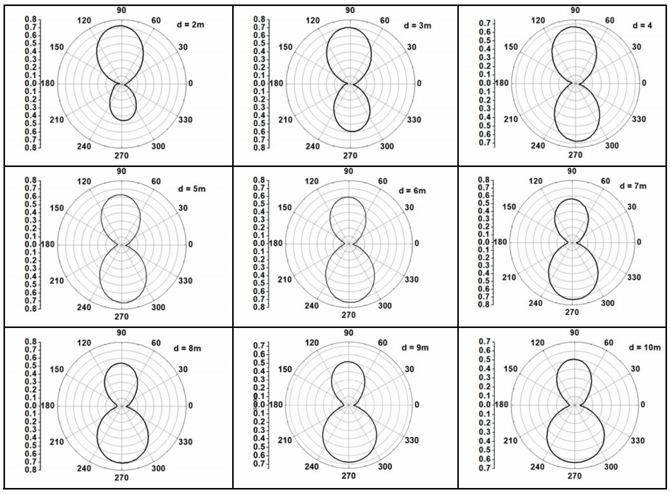

Fig. 7. 2 D radiation pattern with varying helicopter-antenna distances from 2 m to 10 m.

Comparing and analyzing the S11 and radiation plots, the distance from 7 m to 10 m are in the acceptable range for the real time survey. So we can choose the helicopter-antenna distance in these range. The rope length of the antenna hanging below the helicopter is one of the critical component. An optimum rope length is done finally depending upon the selected glacier survey environment for avoiding unwanted ringing effects and blanking of glacier subsurface reflections. Suitable choice of the type of the helicopter, its speed and flight flying altitude above glacier ground surface are also the essential things to be considered for the survey. Here, with the help of the numerical analysis software tool, the placement analysis simulations have been done and by examining the results obtained, the optimum range of helicopter-antenna distances are determined reducing test flight time which is expensive.

6. Conclusion

A simplified procedure to analyze the far fields of a 10 MHz bent wire antenna system is presented. The derived analytical equations of the electric field when plotted is approximately having the same shape as that of the electric field numerically simulated results of the whole antenna structure. From this, it is evident that the modified analytical equation holds well with the HFSS© simulation results of the 10 MHz antenna system. The 10 MHz wire antenna is having bents and parasitic influence for resonating in its respective frequency. So, the presence of bents and parasitic element must be considered in deriving the far field analytical equation for the antenna which is very sensitive and influences the resonant frequency of the antenna system. The optimum placement of the antenna below the helicopter during the GPR field survey must be carefully chosen considering all the three antenna parameters: directivity, radiation pattern and S11 combined together. The proposed analysis using a numerical simulation tool is an efficient method to optimize the range of distances between the low frequency antenna system and the helicopter used for the GPR field survey.

Acknowledgments

This work is carried out as part of Italian Antarctic Research Activity (PNRA Program). The authors are thankful to the SASTRA – Keysight Center of Excellence in RF System Engineering.

References

[1] SCOTT BENNETT, W. A basic theorem that simplifies the analysis of wire antennas. *IEEE Antennas and Propagation Magazine*, 1998, vol. 40, no. 1, p. 22–30. DOI: 10.1109/74.667322

[2] HAMID, M. A. K., BOERNER, W. M., SHAFAI, L., et al. Radiation characteristics of bent-wire antennas. *IEEE Transactions on Electromagnetic Compatibility*, 1970, vol. 12, no. 3, p. 106–111. DOI: 10.1109/TEMC.1970.303078

[3] TSUKIJI, T., TOU, S. On polygonal loop antennas. *IEEE Transactions on Antennas and Propagation*, 1980, vol. 28, no. 4, p. 571–575. DOI: 10.1109/TAP.1980.1142380

[4] EGASHIRA, S., TAGUCHI, M., SAKITANI, A. Consideration on the measurement of current distribution on bent wire antennas. *IEEE Transaction on Antennas and Propagation*, 1988, vol. 36, no. 7, p. 918–926. DOI: 10.1109/8.7196

[5] GOMEZ MARTIN, R., RUBIO BRETONES, A., FERNANDEZ PANTOJA, M. Radiation characteristics of thin-wire V-antennas excited by arbitrary time-dependent currents. *IEEE Transactions on Antennas and Propagation*, 2001, vol. 49, no. 12, p. 1877–1880. DOI: 10.1109/8.982473

[6] CHAN, K. K., SILVESTER, P. Analysis of the log-periodic V-dipole antenna. *IEEE Transactions on Antennas and Propagation*, 1975, vol. 23, no. 3, p. 397–401. DOI: 10.1109/TAP.1975.1141070

[7] KYLE, R. Mutual coupling between log-periodic antennas. *IEEE Transactions on Antennas and Propagation*, 1970, vol. 18, no. 1, p. 15–22. DOI: 10.1109/TAP.1970.1139613

[8] BHATNAGAR, P. S., SACHAN, S. B. L. Analysis of infinite zig-zag antenna. *IEE-IERE Proceedings - India*, 1976, vol. 14, no. 2, p. 44–46. DOI: 10.1049/iipi.1976.0015

[9] SENGUPTA, D. The radiation characteristics of a zig-zag antenna. *IRE Transactions on Antennas and Propagation,* 1958, vol. 6, no. 2, p. 191–194. DOI: 10.1109/TAP.1958.1144571

[10] THIELE, G. A. Analysis of yagi-uda-type antennas. *IEEE Transactions on Antennas and Propagation*, 1969, vol. 17, no. 1, p. 24–31. DOI: 10.1109/TAP.1969.1139356

[11] CHENG, D. K., CHEN, C. A. Optimum element spacings for Yagi-Uda arrays. *IEEE Transactions on Antennas and Propagation*, 1973, vol. 21, no. 5, p. 615–623. DOI: 10.1109/TAP.1973.1140551

[12] WALKINSHAW, W. Theoretical treatment of short Yagi aerials. *Journal of the Institution of Electrical Engineers - Part IIIA: Radiolocation*, 1946, vol. 93, no. 3, p. 598–614. DOI: 10.1049/ji-3a-1.1946.0148

[13] KING, R. W. P. The linear antenna-eighty years of progress. *Proceedings of the IEEE,* 1967, vol. 55, no. 1, p. 2–16. DOI: 10.1109/PROC.1967.5373

[14] NAKANO, H., YAMAUCHI, J., NOGAMI, K. Effects of wire radius and arm bend on a rectangular spiral antenna. *Electronics Letters,* 1983, vol. 19, no. 23, p. 957–958. DOI: 10.1049/el:19830651

[15] NAKANO, H., MINEGISHI, Y., HIROSE, K. Effects of feed wire on radiation characteristics of a dual spiral antenna. *Electronics Letters,* 1988, vol. 24, no. 6, p. 363–364. DOI: 10.1049/el:19880246

[16] CHAO, H., STRAIT, B., TAYLOR, C. Radiation and scattering by configurations of bent wires with junctions. *IEEE Transactions on Antennas and Propagation,* 1971, vol. 19, no. 5, p. 701–702. DOI: 10.1109/TAP.1971.1140021

[17] FANTE, R., HAZARD, K., DOLAN, J. RCS of bent wires. *IEEE Transactions on Antennas and Propagation,* 1968, vol. 16, no. 1, p. 130–132. DOI: 10.1109/TAP.1968.1139098

[18] SHLIVINSKI, A., HEYMAN, E., KASTNER, R. Antenna characterization in the time domain. *IEEE Transactions on Antennas and Propagation,* 1997, vol. 45, no. 7, p. 1140–1149. DOI: 10.1109/8.596907

[19] SIAKAVARA, K., SAHALOS, J. N. A simplification of the synthesis of parallel wire antenna arrays. *IEEE Transactions on Antennas and Propagation,* 1989, vol. 37, no. 7, p. 936–940. DOI: 10.1109/8.29388

[20] SUGANYA, J., SCIACCA, U., BASKARADAS, J. A., et al. Analysis of bent wire antenna resonant frequency for different bent angles. *Radio Science*, 2019, vol. 54, no. 12, p. 1240–1251. DOI: 10.1029/2019RS006906

[21] URBINI, S., CAFARELLA, L., TABACCO, I. E., et al. RES signatures of ice bottom near to Dome C (Antarctica). *IEEE Transactions on Geoscience and Remote Sensing*, 2015, vol. 53, no. 3, p. 1558–1564. DOI: 10.1109/TGRS.2014.2345457

[22] URBINI, S., ZIRIZZOTTI, A., BASKARADAS, J. A., et al. Airborne Radio Echo Sounding (RES) measures on Alpine glaciers to evaluate ice thickness and bedrock geometry: Preliminary results from pilot tests performed in the Ortles Cevedale Group (Italian Alps). *Annals of Geophysics*, 2017, vol. 60, no. 2, p. 1–12. DOI: 10.4401/ag-7122

About the Authors...

SUGANYA Jayaraman was born in 1985. She received her BE degree in ECE from Arasu Engineering College and ME degree in Communication Systems from Bannari Amman Institute of Technology, affiliated to Anna University, Tamilnadu, India in 2006 and 2008 respectively. She worked in SRC, SASTRA Deemed University as Assistant Professor - II from 2008 to 2011. Currently, she is doing her full time PhD in SASTRA Deemed to be University in the area of Radio Systems and Antennas. Her research interests include electromagnetics, antennas, microwave engineering.

James A. BASKARADAS (corresponding author) received his PhD (2001) from Nagpur University, India. He did his Post Doc. at the Istituto Nazionale Di Geofisica e Vulcanologia (INGV), Rome, Italy and continued as

Research Technologist at the same institute (2001 – 2014). His research interests are in radar instrumentation and remote sensing of ionosphere and glaciers. He has over 20 publications and two patents. He participated in two Italian Antarctic expeditions for radar remote sensing. At present he is working as the Senior Assistant Professor at SASTRA Deemed University, India.

Umberto SCIACCA received his Masters. in Electronic Engineering at "Sapienza" University of Rome in 1989, following a remote sensing curriculum. He spent some years as a designer of electronic equipments in the space industry. Now he is a Senior Technologist at Istituto Nazionale di Geofisica e Vulcanologia, Rome (the Italian institution for Geophysics). His main activities include: feasibility studies on the remote sensing electronic systems; design, engineering and test of radar-based instrumentation to be used in geophysical applications (above all ionospheric sounders and radars for glacier prospecting).

Achille ZIRIZZOTTI received his Masters degree in Physics at "Sapienza" University of Rome in 1991 and joined Istituto Nazionale di Geofisica e Vulcanologia (INGV) in 1997. Now he is a Senior Research Technologist at the INGV. Since 1997 he has been working on glaciological radar as a Technologist at the INGV. The basic research interests are environmental geophysics, glaciology, radar science in geophysics and glaciology. He was principal investigator and co-investigator of five Italian Antarctic projects, developing Radio Echo Sounding (RES) Systems widely used in Antarctica by the Italian group and principal Coordinator of the Italian Radio Echo Sounding Database (IRES database). He participated in eleven Antarctic expeditions from 1997 to 2015, collecting over thirty thousand kilometers of radar data in various projects (evaluation of the ice mass balance, determination of the drilling point of Epica project, Dome C ice conditions of the bedrock and subglacial lakes exploration).