Study of Propagation of Ultra-Wide Band Electromagnetic Pulse through a Dispersive Soil Medium for the Detection of Buried Unexploded Ordnance

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Abstract— **Buried Unexploded ordnance (UXO) poses a serious humanitarian problem. At Present, there is no single equipment/system available to detect the unexploded buried ordnance (UXO), which fully satisfies the United Nations Mine Action Standard (UNMAS) requirements for safe removal and disposal of such ordnance. This paper presents the importance of the soil electrical characteristics and its electromagnetic model in the detection of buried UXO. Frequency domain analysis of EM wave propagation in the lossy dispersive soil media is carried out to study the detection range of the buried target. It is found that for the soil conductivity below 2 mS/m, effect of conductivity on EM wave attenuation in the moist soil can be neglected for the frequency of interest (3-5GHz). From the analysis, incident wave bandwidth between 3-5 GHz offers nominal ground penetrating imaging capability with nominal detection range in the soil media. Studies were carried out to find the importance of dispersive soil dielectric model against the constant permittivity model in the simulation of landmine detection system. Double Debye model is used to model the dielectric permittivity of the soil, Weighted Least Square (WLS) method is used to find the unknown parameters in the Double Debye model using the experimental results available in the literature. It is found that WLS model offers better performance for a wide band spectra dielectric model of the soil. One dimensional Finite Difference Time Domain method (FDTD) along with Piecewise Linear Recursive Convolution (PLRC) is used to simulate the system.**

Keywords—Unexploded Ordnance (UXO), Ultra-wide Band (UWB), Pulsed EM Field, Electromagnetic(EM) wave.

I. INTRODUCTION

Conflicts between nations are increasing across the globe and remnants of the past conflicts have left behind around 110 million unexploded landmines, which are lodged in the ground. Every year more than 4,000 people lose their life/limbs around the world due to these landmines. As per UNICEF, in 2014 year alone around 487 children have lost their life in Afghanistan. It is reported that for every 2000 mines cleared, one deminer loses his life. So there is an urgent need for developing new equipment/technologies for efficient and reliable detection of buried unexploded landmines.

A. United Nations Requirements

As per the International Mine Action Standards (IMAS), humanitarian demining of land mines require 99.96% success rate with an accuracy of finding object of size 4cm, which are buried at a depth of 10-20 cm with thes localization ability of 0.5 m. As per United Nations guidelines, while designing the system, 8 years of soil accumulation and plant growth after the mines have been laid also have to be considered. This requirement goes beyond just target detection. This calls for target identification/classification to avoid detection failure and false alarm. So there is a need for subsurface imaging of the target. Subsurface imaging and target identification requires very high range and plan resolution for the entire possible buried depth in all lossy soil condition. At present, there is no mine detection system available, which satisfies all the United Nations guidelines and the research on reliable, low cost, all weather landmine detection systems are the need of the hour.

B. Principle of EM pulse Detection of UXO/Landmine

Buried UXO are detected based on reflection of the incident EM wave from the buried UXO/Landmine. This is possible because of the differences in the permittivity between the host soil medium and the buried mines. Range of detection is severally affected by the attenuation in the soil medium due to its moisture content.

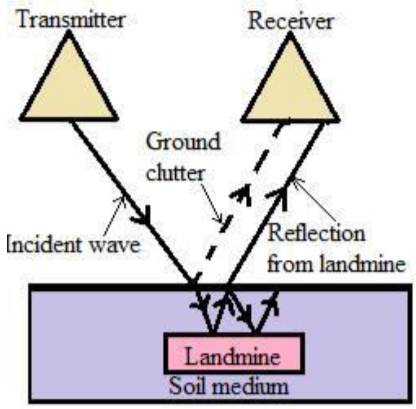

Figure 1 Principle of EM wave detection of UXO

Complexity in the mine detection system like high clutter, low signal to noise ratio, complex soil medium and environment variation calls for an accurate computer simulation of the whole system for various ground conditions. Ground penetrating Radar (GPR) with the incident wave frequency of 1-2 GHz offers better detection range, but has poor detection resolution. So it is difficult to find the dimension of buried target and depth of burial of the landmine. Remote sensing imaging radar satellite uses K, Ka and Ku band, which offer better resolution but has very less detection range. So GPR imaging radar with the frequency band in between normal GPR and remote sensing satellite is an obvious choice for obtaining nominal detection range and resolution. This paper studies the effect of soil characteristics using the incident EM wave with a bandwidth of 20 GHz.

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II. METHODLOGY

Design of anti-personal mine detection system is influenced by input signal, antenna design, soil condition, terrain condition, target characteristics, receiver bandwidth, clutter levels and signal processing tools. Selection of incident EM wave has many challenges, wherein tradeoff between accuracy and practicality has to be achieved without comprising the detection capability. Incident signal bandwidth, polarization, power, incident angle and beam width has a direct impact on the detection capability of the system. Detailed computational simulation has to be carried out to select the appropriate incident signal parameters. Although practical system requires three dimensional computational simulations, it is really difficult to analyze all the input parameters in three dimensional electromagnetic simulations. So, before attempting the three dimensional computation, one has to perform detailed study of the approximate system using one dimensional simulation. One dimensional FDTD simulation provides a detailed and basic idea on the importance of incident wave bandwidth and power level for subsurface detection.

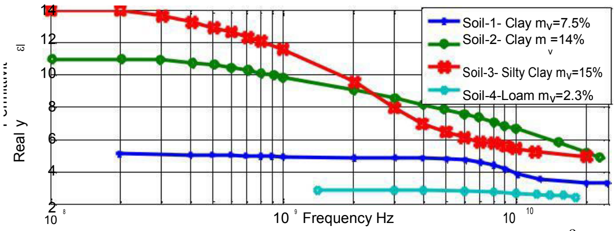
Though higher frequency offers better resolution but it has higher attenuation in the soil media. Hence it has very less detection range. This paper studies the propagation characteristics of incident EM wave of different bandwidth on the various soil medium. One of the most important aspects of any subsurface detection system lies in the understanding of the soil medium, so detailed study on the electrical properties of the soil has been carried out.

III. CHARACTERISTIC STUDY OF THE SOIL MEDIUM

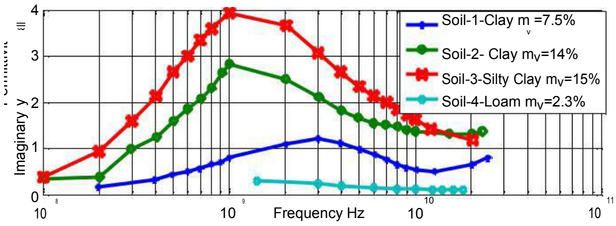
Soil in general is a multi-phase medium, contains solid particle, air and moisture (bulk water and free water). Presence of dipolar element like water makes soil a dispersive medium, which leads to different relaxation phenomenon. In general soil has three important polarizations, they are Maxwell-Wagner polarization, bound water dipolar polarization, free water dipolar polarization and they are active in different frequency ranges. Water in soil makes it colloidal and dispersive in nature. Due to the complicated structure of the soil, it is difficult to deduce a proper electrical model for it. Soil dielectric property depends on its physical structure/texture (sand, silt, clay content), moisture content, temperature, frequency, porosity and salinity.

A. Dispersive Dielectric Modelling of the Soil Medium

Electrical conductivity and complex dielectric permittivity of the soil affects the EM wave propagation in the soil medium, so it is very important to model these properties of the soil medium. Considerable studies have been carried out for the measurement of soil dielectric permittivity and conductivity for the different moisture content and soil type at various frequencies. Smith Rose [1], Hokekstra and Delaney [2], Hallikainen, Ulaby et al[3]. John O.Curtis[4] et al[4] and many others have conducted extensive measurement of soil permittivity and conductivity for various frequency band, temperature, soil type and moisture content. Extensive research have been carried out to theoretically model the complex dielectric permittivity of the soil, but all these available theoretical models have its own limitations. At present, no single model is available, which can consider the effects of the soil moisture and texture for a wide range of frequency spectrum. Wobschall[5], Dobson et al[6], Wang and Schmugge[7], Boyarskii[8] and many others derived a theoretical model of the soil considering the bound water. Deloor[9] showed that it is impossible to develop a theoretically accurate dielectric model for the soil, so Deloor proposed a bound for the complex dielectric permittivity. Due to the lack of better theoretical model many researchers proposed empirical [6,2] and semi empirical model [10] for the soil, in this work phenomenological model called Double Debye model is used to study the dielectric properties of the soil using experimental results available in the literature [2][3][4] and these data are shown in fig.1.



(a) Measured Real Permittivity of the Soils used in the Simulation at Temperature=24°C



(b) Measured Imaginary Permittivity of the Soils used in the Simulation at Temperature=24°C

Fig.1. Measured real and imaginary permittivity of the Clay and Silty-Clay Soil [2][3][4]

In the present work, complex permittivity( ) of the soil is modeled using Double Debye model as given by eq.1 with six unknown parameters, static permittivity ( ), high frequency permittivity ( ), two relaxation times ( ), high frequency conductivity ( ) and interpolation constant (C).

( ) ( )( ) (1)

(2)

Weighted least square method is used to find the unknown parameter in the double Debye model based on the experimental data available in the literature.

B. Weighted least square (WLS) method for Soil Modelling

Six unknown parameters( ) of Double Debye model for a particular soil type and moisture content was found using weighted least square method [11]. Every measurement has its own error associated with it, so dielectric measurement of the soil normally has more than 5% error due to the variation in the measurement technique and complexities involved in maintaining the dry density, temperature, moisture content of the soil over the period of measurements. So very accurate fitting of Double Debye model with the experimental measurement have no practical significance. Weights can be assigned to each measurement based on the experimental technique and hardware ability of the setup. Weights also provide better flexibility in choosing the best fit for the given measurement. Not many literatures are available, which measures the dielectric property of the soil for wide frequency spectrum, soil moisture, temperature and soil type, so weights can be used to merge two different measurement of the same soil.

The above solution have many local minima. So initial conditions play an important role in the better fit. Graphically viewing the intermittent result will help set the better initial conditions. Also bound/limit should be applied to each unknown to avoid divergence of the solution. Table-1 shows the value of unknown parameter obtained in the WLS method for different soils, which is used to simulate the soil media. Figure.2 compares the measured dielectric permittivity with the interpolated value.

Table 1: Soil details and its various unknown parameters estimated using WLS method from the experimental data for all soils, .

Soil Name	Soil Texture	Moisture Content%			C		
Soil-1	Clay	7.5	3.53	5.66	0.01	2.0E-9	5.81E-11
Soil-2	Clay	14	5.82	11.15	0.57	1.04E-10	1.14E-10
Soil-3	Silty Clay	15	5.53	14	0.01	2.0E-9	1.03E-10
Soil-4	Loam	2.3	2.58	3.07	0.01	1.0E-9	8.09E-11

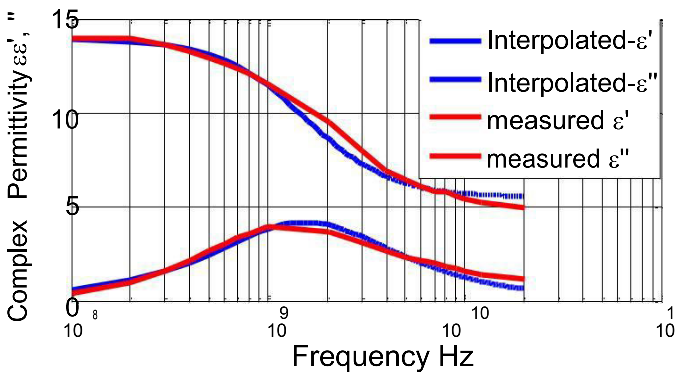


Fig.2. Soil-3 permittivity obtained using WLS and measured permittivity

C. *Study of Soil Electrical Parameters*

Soil conductivity and permittivity depends on its moisture content and soil texture. It is very important to study these parameters in detail. Attenuation of the plane EM wave on a homogeneous medium is given by Eq.3.

Fig.4 shows the importance of the electrical conductivity of √((√ * +)) (3) the soil. For a conductivity of 12 mS/m at 2 GHz, contribution of conductivity on attenuation (200 dB/m) is roughly equal to the attenuation due to relaxation imaginary permittivity, but it

– (4)

— (5)

Loss permittivity or effective imaginary permittivity contains two components one due to dielectric relaxation and another due to DC electrical conductivity as given in the eq.5.

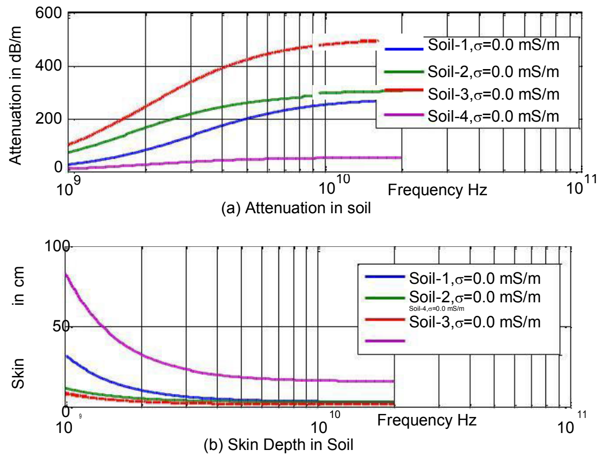


Fig.3. Attenuation of EM wave for Clay and Silty clay soil

As shown in Fig.3, attenuation of the EM wave increases with increase in imaginary effective permittivity and frequency. Fig.3 (b) shows the soil skin depth for various soil type and frequency. Many researchers observed that, effect of conductivity is negligible for high frequency wave but it is observed that higher DC conductivity offer considerable attenuation of EM wave. It is found that for the frequency range above 500 MHz conductivity above 40 mS/m offers considerable contribution to effective imaginary permittivity. Since mine detection need really high success rate in all-weather condition, It is important to study the electrical conductivity of various soil media. Soil conductivity is highly dependent on soil texture. Clay soil contains very high conductivity than sandy soil. Soil conductivity can vary from 0 to 1000 mS/m [12]. Normally most of the soil have conductivity variation from 0-100 mS/m. Conductivity of 100 mS/m have significant impact in attenuation at high frequency.

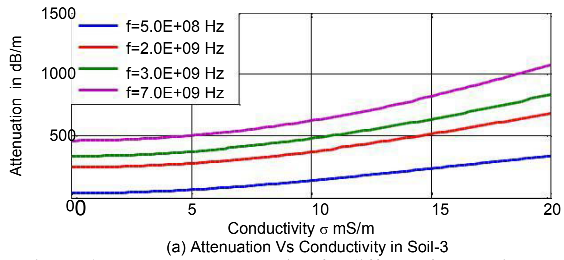


Fig.4. Plane EM wave attenuation for different frequencies and conductivities

is negligible for conductivity less than 2 mS/m. So conductivity can't be totally ignored for the frequency (300MHz to 5GHz) of interest for mine detection.

IV. FDTD Formulation of the Mine Detection System

One dimensional Finite Difference Time Domain (FDTD) method [13] is used to simulate the system. Dispersive characteristics of the soil medium is implemented by using Piecewise linear recursive convolution technique (PLRC). Dielectric property of the soil is modeled by Double Debye (contains two relaxation time) relaxation model. Scattered field/Total field (SF/TF) method is used to inject the input EM plane wave. Uni-axial perfectly matched layer (UPML)[14] with polynomial conductivity profile is used to truncate the domain.

() () () ( ) ()( ) (6)

Double Debye model in time domain

() () ( )* / ( ) / + (7)

Fig.5. 1D-FDTD system simulation Domain

Block diagram of the one dimensional system is shown in the figure.5. Landmine is modeled as a non-dispersive medium of constant relative permittivity of . Simulations were carried out for different soils of varying soil depth for different incident EM wave bandwidth and magnitude.

A. Input Electric Field Signal

Sinc function time domain EM wave represented by eq.8 is used to study the propagation of EM wave on the soil medium. Sinc function as shown in the fig.6 is chosen because of its exact low pass frequency characteristics. So it is easy to study the frequency domain response of the soil medium using band limited EM signal of a particular bandwidth (B). Here studies were carried out for incident EM wave of bandwidth B=20 GHz

() (V/m (8).

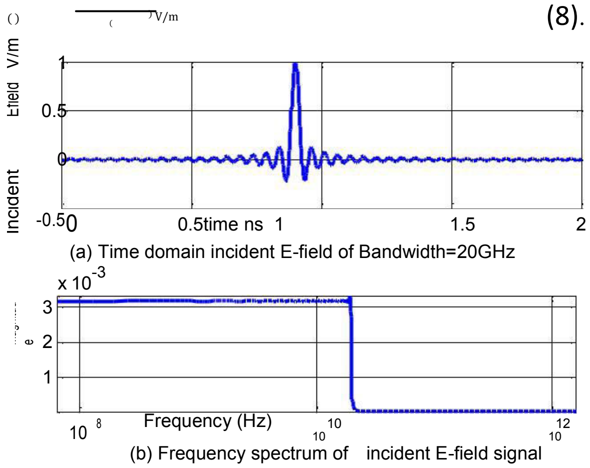


Fig.6. Incident time domain E-field and its frequency spectrum

V. Frequency Domain Analysis of the Soil

This section studies propagation of incident EM wave in the soil media. Sinc function electric field of different bandwidth is incident into the soil medium. Measurements were carried out at differing depth of the soil and its frequency domain analysis was carried out to study the bandwidth of the transmitted signal at different depth of propagation into the soil. This provides a better picture of the detection range of the system. Though large bandwidth offers better resolution, but due to the high frequency attenuation it has very less detection range. So there is need to find a tradeoff between depth resolution and detection range. Impact of high power EM wave on landmine detection is also studied. Purpose of this study is to find an initial estimate of the incident E-field bandwidth required for better detection. Soil with the medium volumetric moisture content (=15%) with the conductivity of 5 mS/m is used to simulate the system.

A. EM Wave Propagation in the Soil Medium

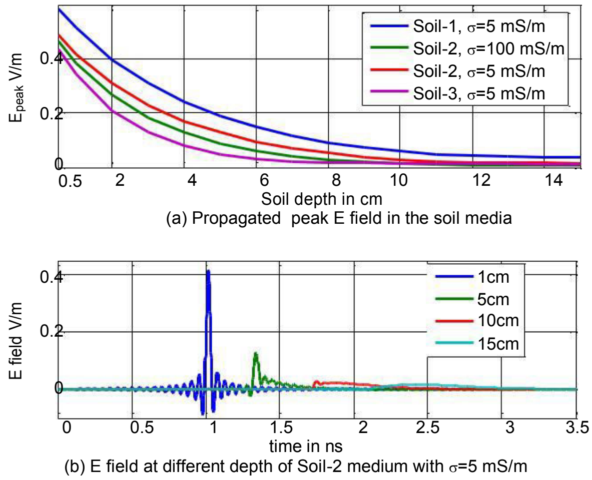


Fig.7. Peak electric field and time domain E field for varying soil depth

As shown in fig.7, magnitude of the E-field decreases exponentially as it propagates through the soil. High conductivity (100 mS/m) has a considerable impact on the peak value of electric field till certain soil depth, for higher depth, around 10 cm, conductivity has a negligible impact, and it is due to the reduction in the maximum frequency content in the E-field. Figure.8 shows the normalized transmitted E field spectrum with respect to incident EM wave spectrum at the start of the soil medium.

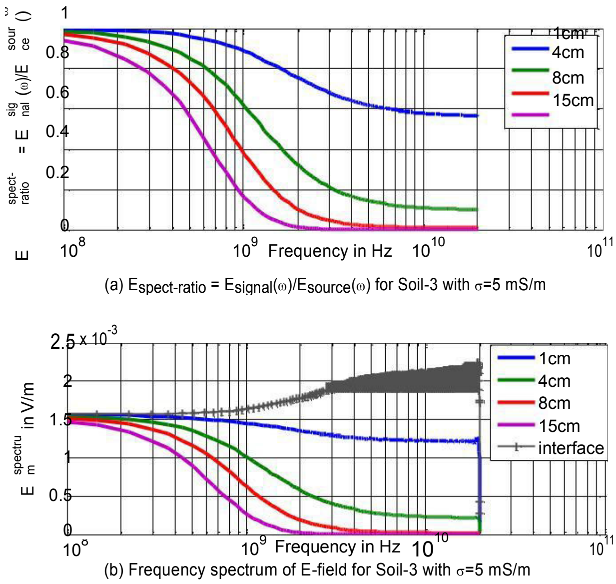
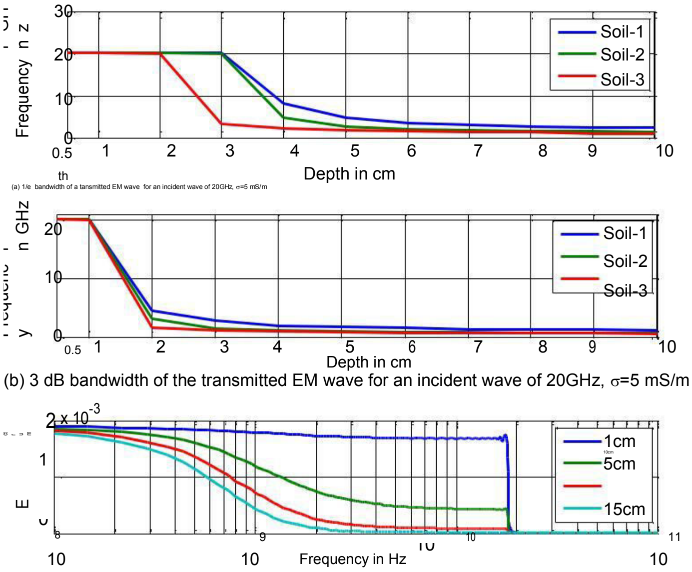


Fig.8. Normalized and actual E field spectrum for various soil depth

As shown in Fig.9, for Soil-3 with a moisture content of 15%, it is found that, irrespective of incident E-field signal bandwidth, transmitted E-field signal for a depth beyond 4 cm has bandwidth less than 2 GHz. Much of the high frequency content of the E-field attenuated within 4cm. It never reached higher depth and so high power loss of the signal in the first few centimeter depths leading to less efficiency in detection. Efficiency factor can't be overlooked since high frequency contents are important on low soil depths to get a better detection resolution.



(b) 3 dB bandwidth of the transmitted EM wave for an incident wave of 20GHz, σ=5 mS/m

(c) Frequency spectrum of the transmitted E-field for Soil-2 with σ=5 mS/m

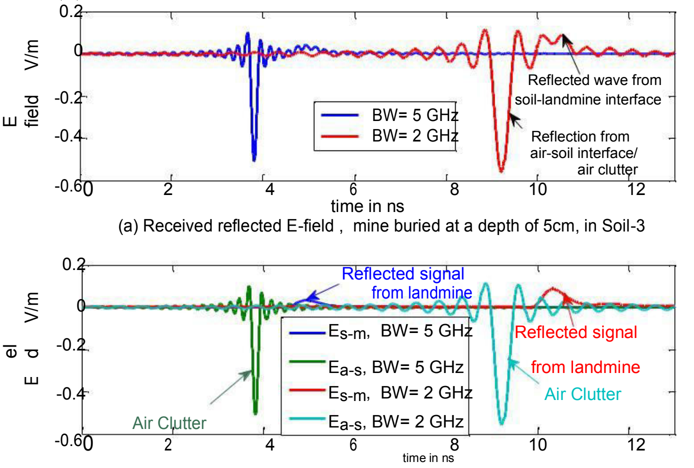
Fig. 9. Maximum frequency in the Transmitted E-field in 15% moisture soil

There is a difference in opinion on defining the bandwidth of the E-field signal because it depends on the detectability and bandwidth of the receiver. Fig.10, shows the maximum frequency content of the transmitted signal in two different ways, fig. 9 (a) shows the maximum frequency content as the

() – . It shows that for the depth beyond 4cm, maximum transmitted frequency is about 3-4 GHz irrespective of the input bandwidth (peak E-field). Fig.9 (b) shows the conventional maximum frequency based on half power bandwidth. It shows that 2 GHz is a maximum frequency for a depth beyond 4cm for 15% moisture soil. So use of frequencies above 5 GHz has no significant advantage at soil depths beyond 2 cm. These results should be combined with frequency spectrum analysis of reflected E-field signal from the soil-mine interface to find a tradeoff between bandwidth and depth resolution.

VI. DISPERSIVE SOIL MODEL IN LANDMINE DETECTION

This section studies the importance of a dispersive model for simulating the landmine detection system by comparing it with the results obtained from the constant low frequency permittivity soil model. One dimensional landmine detection system as shown in fig.5 is simulated for different burial depth of landmine. Received reflected wave as shown in the fig.10 (a) contains reflected wave from air-soil interface (air clutter) and soil-landmine top interface. Reflected wave from soil-landmine interface is used to detect the buried landmine, so reflected signal from landmine obtained by back subtracting received signal with the simulated air clutter as shown the fig. 10(b).



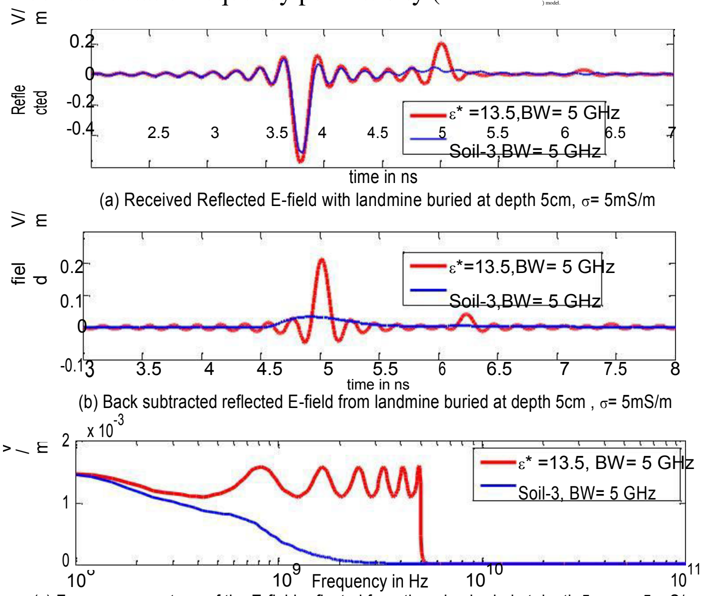
(a) Received reflected E-field , mine buried at a depth of 5cm, in Soil-3

(b) Back subtracted air clutter ($E_{a\text{-}s}$) & reflected E-Field ($E_{s\text{-}m}$) from soil-mine interface

Fig.10 Reflected E-field for landmine buried at a depth of 5cm in Soil-3 with

Figure.11 shows the received E-field wave obtained in the

simulation using Double Debye dispersive soil model and constant static frequency permittivity ( ) model.



(a) Received Reflected E-field with landmine buried at depth 5cm, σ= 5mS/m

(b) Back subtracted reflected E-field from landmine buried at depth 5cm , σ= 5mS/m

(c) Frequency spectrum of the E-field reflected from the mine buried at depth 5 cm,σ= 5 mS/m

Fig.11. Reflected EM wave from constant permittivity soil medium and dispersive soil medium

From the Fig.11, reflected EM wave considering dispersive soil model has totally different E-field shape and frequency content than constant permittivity soil model. Low frequency constant soil permittivity model overestimate the resolution and detection ranges. So simulation of the landmine detection system, for the frequency of interest has to be carried out by considering the dispersive nature of the soil.

VII. Conclusion

Soil is modeled using Double Debye model and its six unknown parameters are found from the experimental value using weighted least square method. WLS offers the better flexibility in interpolating the measured data obtained from various experimental setups. Detailed study on effect of soil conductivity on the landmine detection has been carried out. For a soil with the conductivity below 2mS/m, the effect of attenuation due to conductivity for the frequency of interest (500MHz to 5GHz) is negligible as compared to the loss due to dielectric relaxation. For a soil with medium moisture content, EM wave signal propagated beyond 2cm in the soil medium has maximum frequency content independent of the incident EM wave bandwidth. Accurate soil dielectric model is required to simulate the landmine detection system. Constant permittivity soil model leads to totally erroneous results. So dispersive nature of the soil have to be included in the simulation.

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