DEVELOPMENT OF DIELECTRIC-FILLED TEM HORN ANTENNAS FOR UWB GPR

B. Scheers (1) **, M. Piette** (1) **, A. Vander Vorst** (2)

(1) ***RMA, Department ELTE***
30, Avenue de la Renaissance, B-1000 Brussels
Email: bart.scheers@elec.rma.ac.be / marc.piette@tele.rma.ac.be

(2) ***Hyperfréquences U.C.L., Belgium***
Email: vandervorst@emic.ucl.ac.be

INTRODUCTION

The Ground Penetrating Radar (GPR) is one of the most promising technologies for close detection and identification of buried landmines. Conventional GPRs however are mostly designed for geophysical applications and use central frequencies up to 1GHz. As landmines are small objects, a large bandwidth is needed for a better depth resolution. During trials with commercial GPR systems on minefields containing inert AP mines, we evaluated two types of antennas : element antennas, that have to be in contact with the ground and horn antennas that can operate off ground. Although these conventional antennas proved their use in GPR applications, none of them can be used for demining applications. So there is a need for new types of antennas. From this experience and taking into account the UWB approach, we decided to develop our own antennas with the following technical and practical design goals: the antennas have to be very small, non-dispersive, with a high directivity to be able to couple sufficient energy into the ground when used off ground, and radiating efficiently over a large bandwidth (between 500MHz and 4GHz). We also want them to be cheap in production. One of the most promising antennas that can meet these design goals is the travelling wave TEM horn.

THE TEM HORN

In an effort to increase the directivity or the antenna gain for a broadband and non-dispersive antenna, many researchers have considered a TEM horn. A travelling wave TEM horn consists of a pair of triangular conductors forming a V structure (Fig. 1), capable of radiating and receiving a fast transient pulse [1]. It is assumed that the TEM horn guides essentially the TEM mode within the frequency range of interest by maintaining a constant characteristic impedance and that, by neglecting the edge diffraction effect and fringe fields, a linearly polarised spherical wave is radiated.
The conventional design of the TEM horn is based on the infinitely long biconical antenna. Many variants are possible, e.g. resistive loading of the antenna [1], tapering the antenna plates, gradually changing the separation angle between the antenna plates [2], or placing a dielectric lens at the aperture [3]. A conventional TEM horn is completely characterised by three parameters: L the length of the antenna plates, φ_0 the azimuth half-angle, and θ_0 the elevation half-angle. The characteristic impedance of an infinite long TEM horn (L=∞) is only function of the two angles φ_0 and θ_0. Theoretically a TEM mode does not have an upper cut-off frequency, in practice however this upper cut-off frequency will be limited. The dimension L of the antenna mainly governs the lower cut-off frequency.

A MODEL FOR AIR-FILLED TEM HORN

A simple low frequency model for the air-filled TEM horn consists in approximating the antenna by a succession of electric and magnetic dipoles, and summing their contribution [4]. A more accurate model of the TEM Horn is found in the wire method, where the antenna plates are replaced by a set of wires [5]. The transient electromagnetic field emitted by a TEM horn antenna is the sum of the transient electromagnetic fields emitted by each individual wire. The wire method is a time-domain-based method. For the model some assumptions are made. The current on the antenna plates is strictly radial and travels with the speed of light. The waveform and amplitude of the travelling current is constant along the wire. In this model, the characteristic impedance along an infinite TEM horn (L=∞) or the early-time surge impedance (for L< ∞), is given by:

$$Z = \frac{Z_0}{4\pi}\sum_{i=1}^{N}\left[\ln\frac{1-\cos\varphi_i\cos 2\theta_i}{1-\cos\varphi_i}\int_{\varphi_i-\Delta\varphi/2}^{\varphi_i+\Delta\varphi/2}F(\varphi,\varphi_0)\,d\varphi\right], \tag{1}$$

with $F(\varphi,\varphi_0)=1\big/\pi\sqrt{\varphi_0^2-\varphi^2}$ the azimuth current distribution on the antenna plates, N the number of wires of the wire mesh, φ_i and θ_i the azimuth and elevation angle of the i^{th} wire, $\Delta\varphi$ the angle between the wires and $Z_0=120\pi$. The wire method turns out to be very accurate for predicting the surge impedance, the half-power beamwidth in the H-plane and the bandwidth of the air-filled TEM horn. In Fig.2, we compare the surge impedance calculated by (1) with the surge impedance measured by time domain reflectometry (TDR). The small discrepancy is probably due to the fact that the wave guided by the antenna plates is actually not purely TEM. The number of wires N used in the wire model is 400.

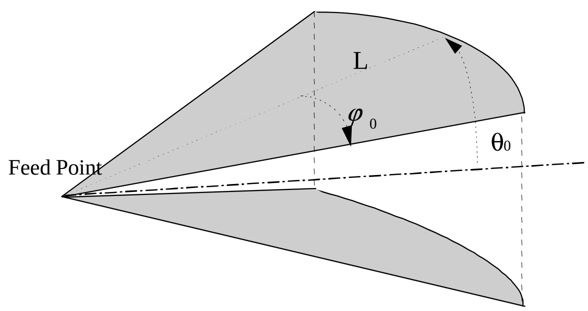

Fig. 1. conventional design of the TEM horn antenna

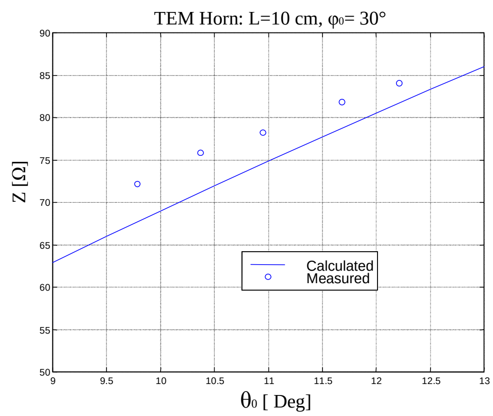

Fig. 2. Measured and calculated surge impedance of air-filled TEM horn

In the design phase of the air-filled TEM horn, we used the wire model to optimise the angle φ_0 for given L and surge impedance of the antenna. Indeed, given the surge impedance, a set of couples (φ_0, θ_0) can be calculated using (1). For each couple, the radiated transient electromagnetic field can be calculated and compared. Doing so, the optimal angle φ_0 for a surge impedance of 50 Ω, is found to be 30-40 degrees.

THE DESIGN OF A DIELECTRIC-FILLED TEM HORN

In order to improve directivity and to reduce the physical size of the antenna without limiting too much the bandwidth, the TEM horns are filled with a silicone, characterised by a real relative permittivity ε_r of 2.89 and a loss tangent of 0.0084 at 1 GHz. Thanks to the silicone, the propagation speed of the TEM wave between the antenna plates will be divided by $\sqrt{\varepsilon_r}$, or the electrical length of the antenna will be extended by a factor $\sqrt{\varepsilon_r}$. Assuming that the antenna guides a pure TEM wave, the dielectric filling will also reduce the surge impedance of the antenna by a factor $\sqrt{\varepsilon_r}$. To preserve the same surge impedance as before the filling, one can increase the angle θ_0, which means again an improvement of directivity. In the design, the antenna impedance is chosen to match the 50 Ω driving cable. Doing so, the part of the transient travelling current that bounces back at the antenna aperture towards the excitation source, will meet no mismatches on its way back and antenna ringing will be avoided. The principle seems to work well for frequencies in the band of the antenna. According to the optimal apex half-angle of the air-filled TEM horn (see previous Section), the angle φ_0 is chosen to be 30° and the physical length L of the antenna plates to be 12 cm. The antenna plates are etched on a printed circuit board. Inspired by the wire model, the antenna plates are replaced by a set of 41 wires (Fig.3). The distance between the wires is too small to influence the antenna characteristics, but it forces the currents to be radial and it limits the surface of conducting metal. The latter is very important, when using the antennas in combination with a metal detector.

Feeding the TEM horn in its balanced configuration (Fig 1) with an unbalanced coaxial feedline, requires an ultra-wideband (frequency-independent) balun in order to avoid currents on the coax. In previous realisations of a TEM horn, measurements revealed an unbalanced current component on the coax exterior, reflected by the antenna feed. As a consequence, the coaxial feedline was also acting as an antenna. These currents can be suppressed by putting chokes (ferrite cylinders) around the feeding cable [6]. In our design we tried out a new kind of balun. The principle of this balun is based upon an electrostatic reasoning [7]. The taper in the bottom plate provides a gradual transition between an unbalanced set-up, i.e. the upper antenna plate on a groundplane, towards a balanced configuration with two symmetrical antenna plates. Unfortunately, this transition will introduce a slide change of the surge impedance along the antenna. The surge impedance of one antenna plate on a groundplane is half the value found by using (1). On the other hand, the elevation half-angle θ_0 in the unbalanced configuration is measured from the ground plane (Fig. 4.), so will be double of the elevation half-angle of the balanced configuration. In total, the surge impedance of the unbalanced part is found to be a little inferior to the surge impedance of the balanced part of the antenna. Using expression (1), taking into account the reduction of the surge impedance due to the filling and taking into account the influence of the balun, an elevation half-angle θ_0 (defined in the balanced part) of 14.5° is calculated to match 50 Ω. This means a surge impedance of the balanced part of 56 Ω. Summarised, we have L=12 cm, φ_0 =30° and θ_0 =14.5°, which leads to a physical antenna aperture of 12cm by 6cm. Finally, we placed some RAM on the outer side of the antenna plates to reduce the low-frequency ringing in the antenna.

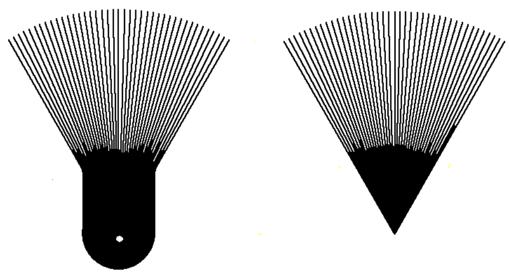

Fig. 3. Lower and upper antenna plates, etched on a PCB.

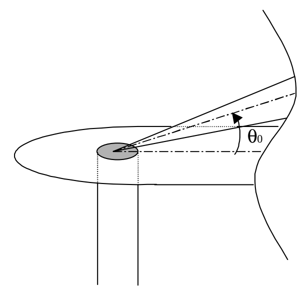

Fig. 4. The ultra-wideband balun

RESULTS OF THE DIELECTRIC-FILLED TEM HORN

Fig. 5. illustrates the surge impedance, measured by time domain reflectometry, along the antenna. Note that the x-axis is calibrated for speed of light. The gradual transition between the unbalanced part (surge impedance around 55Ω) and the balanced part (surge impedance around 65Ω) is obvious. The reduction of surge impedance due to the filling is found to be less than the expected $\sqrt{\varepsilon_r}$, which means probably that the wave, guided by the antenna plates, is not purely TEM. Antenna measurements, performed in the time domain, reveal that the dielectric-filled antennas are more directive. The half-power beamwidth in the H-plane, determined from the peak-to-peak measurement as a function of the angle in the H-plane, is 32°. The lower cut-off frequency, compared to the air-filled antennas, is shifted to the lower frequencies. The actual bandwidth is from 1 GHz up to 5 GHz and is rather flat. So the postulated bandwidth of 500 MHz up to 4 GHz is not reached. However, this can be done by increasing L.

Putting two antennas on boresight for measuring the main beam response, one can notice a small negative pre-pulse. This pre-pulse is due to a TEM mode that goes in the opposite way around the antenna plates and is reduced by the RAM at the outside end of the antenna plates. Fig 6. shows the normalised impulse response on boresight for dominant polarisation of the E-field of the dielectric-filled TEM horn, as defined in [8] (this measurement is performed in the frequency domain using a VNA). In Fig. 6. the pre-pulse is visible. We can also see that the dielectric-filled TEM horn is capable of radiating and receiving very fast transient pulses, without too much ringing. The radiated E-field, evaluated in the far field of the antenna, will fall off by a factor 1/R, called the free space loss, R being the distance between the antenna and the field point. Due to the finite but non-zero dimension of the antenna, this distance R becomes ambiguous near the antenna. Therefore, we defined an apparent point in the antenna, called the "virtual source", from which the 1/R free space loss is initiated. The "virtual source" can be considered as the origin of the radiated impulse TEM wave. The position of this point can be measured experimentally. In our case it is located at 4 cm from the antenna aperture towards the antenna feed and is found to be frequency independent over the frequency band of interest for the dielectric-filled TEM horn.

The dielectric-filled antennas are integrated in a laboratory UWB GPR. Fig. 7. represents an GPR images of a PMN AP mine, buried at 1 cm depth in dry sand, acquired by the UWB GPR. The image is taken by displacing the Tx and Rx antennas by steps of 1 cm (represented on the x-axis). In each antenna position, a short gaussian impulse is radiated and the backscattered signal is recorded (y-axis). This result demonstrates the detection capability of an UWB GPR, equipped with dielectric-filled TEM horns, with regard to shallow buried AP mines.

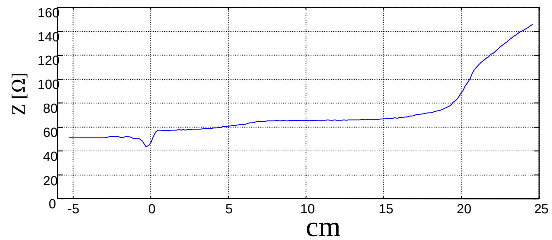

Fig. 5. Surge impedance of dielectric-filled TEM horn, measured by time domain reflectometry

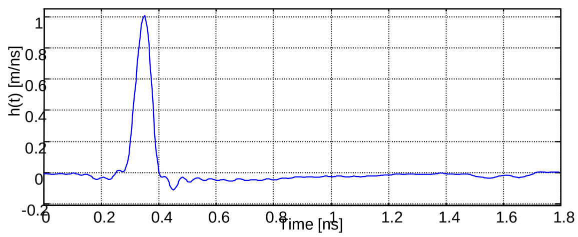

Fig. 6. Normalised impulse response of dielectric-filled TEM horn

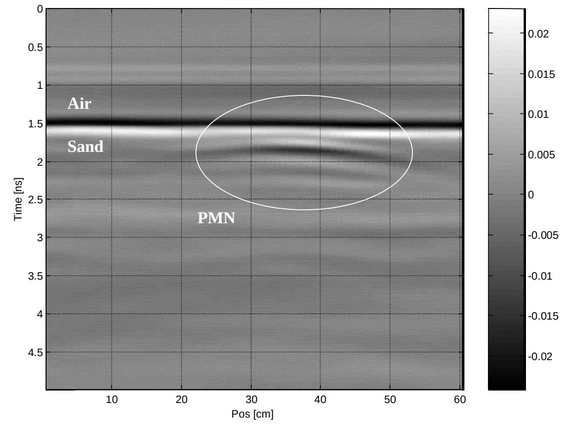

Fig. 7. GPR images of a PMN AP mine, buried at 1 cm depth in sand

CONCLUSIONS

In the research on the detection of buried landmines, we decided to study a new type of UWB GPR antenna. In a first stage an air-filled TEM horn was studied and developed. An accurate model for design purposes was obtained from the wire method. In order to reduce the physical size of the antenna and to improve the directivity, the antenna was filled with a dielectric. Due to the lack of a good model, the design was based on the air-filled antenna, assuming that the antenna guides only a pure TEM wave. TDR measurements of the surge impedance showed a slight but acceptable difference with the calculations. Antenna measurements revealed that the antennas were more directive and that the frequency range moved towards the lower frequencies. The antenna plates were replaced by a set of wires, which make them suitable for operating in combination with a metal detector. An ultra-wideband balun was also integrated in the antenna plates. The dimensions of the dielectric-filled TEM horns are small, as needed for the application, and they are capable of radiating and receiving very fast transient pulses, without to much ringing. The antennas are now integrated, with success, in a laboratory UWB GPR.

REFERENCES

[1] M. Kanda, *Time-Domain Measurements in Electromagnetics*, Edited by E. K. Miller, Van Nostrand Reinhold Company Inc, New York, chap 5, p 122-174, 1986.
[2] A.P. Lambert, S.M. Booker and P.D. Smith, "Transient Antenna Design parameters for optimising Radiated Pulse," AGARD, Electromagnetic Wave Propagation Panel, Proc. 54th Specialists' Meeting on High Power Microwaves, Ottawa, Canada, Chapter 8, May 1994.
[3] J.F. Aurand, "A TEM-Horn Antenna with Dielectric Lens for Fast Impulse Response," *Ultra-Wideband, Short-Pulse Electromagnetics3*, Edited by Baum et al., Plenum Press, New York, pp.113-120, 1997.
[4] E.G. Farr and C.E.Baum, "A Simple Model of Small-Angle TEM Horns," Sensor and Simulation Notes, note 340, 1992.
[5] J.J.A. Klaasen, "An Efficient Method for the Performance Analysis of Bounded-Wave Nuclear EMP Simulators," Sensor and Simulation Notes , note 345, 1992.
[6] C.E.Baum, "Low-Frequency-Compensated TEM Horn," Sensor and Simulation Notes, note 377, 1995.
[7] V.Rumsey, *Frequency independent antennas,* Academic Press Inc, New York, USA, 1966.
[8] E.G. Farr and C.E.Baum, "Time Domain Characterization of Antennas with TEM Feeds," Sensor and Simulation Notes , note 426, 1998.