# The Wave Nature and Propagation Characteristics of the Ground Wave in GPR

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## 1 Introduction

As is well known, the propagation velocity of the GPR (ground penetrating radar) waves depends principally on the relative permittivity of the material. Water, the component which governs the dielectric properties of matter, has a relative dielectric constant of 80 in contrast to the values of 2 to 5 for dry material. So a measure of the dielectric constant in medium is a good measure of its water content. An empirical relationship between relative permittivity and the volumetric moisture was given by Topp et al. (1980), which was found to be nearly independent of soil texture, soil bulk density, and soil salinity. Therefore, GPR waves can be used to determine the water content in the subsurface. But from all the waves propagating between transmitting and receiving antenna, only the ground wave can be best used for this purpose, as it propagates directly in the earth from transmitting to receiving antenna. Many field measurements show that this method to determine water content can overcome the inherent limitations of the present available methods, such as TDR (Time Domain Reflectometry), neutron moderation and others.

In addition to the application mentioned above, the ground wave is also used to acquire the wave velocity for the processing and interpretation of the GPR data, as in many site conditions it may be impossible to get a reference velocity directly from the reflection, due to the conductive loss and/or the interference of the different waves.

However, although the ground wave has been widely used in recent years, its propagation characteristics and physical nature are so far not well studied, nor its influence zone in layered subsurface. Based upon field experiments and theoretical investigation, the wave nature and features of the ground wave are discussed.

## 2 Radiation and Propagation of the GPR Waves

The antennas used in most GPR systems (such as pulse EKKO IV from Sensor & Software inc., etc.) can usually be considered as a horizontal electrical dipole (HED). The radiation of such a dipole source placed on the surface of a half-space is illustrated in Fig. 1. The waves A and B are spherical waves propagating in the air and earth respectively; wave C in the air is an inhomogeneous wave, and wave D in the earth is usually termed lateral wave (Brekhovskikh, 1960). Waves C and D exist only in a limited region, which is defined as those points whose position vectors make an angle greater than the critical angle $\beta$ of the boundary with the z-axis.

The spherical wave B, traveling in the lower medium, has a complementary wave which matches the boundary conditions: An inhomogeneous wave C is produced at the surface; this wave propagates horizontally from the source with the velocity of A, but decays exponentially with the height above the surface. This wave is significant near the surface, but its effect decreases as the receiver moves away from the transmitter.

In the layered subsurface, several waves may reach the receiving antenna. These are the direct air wave, the ground wave, the reflected waves, the critically refracted wave and the ordinary refracted wave.

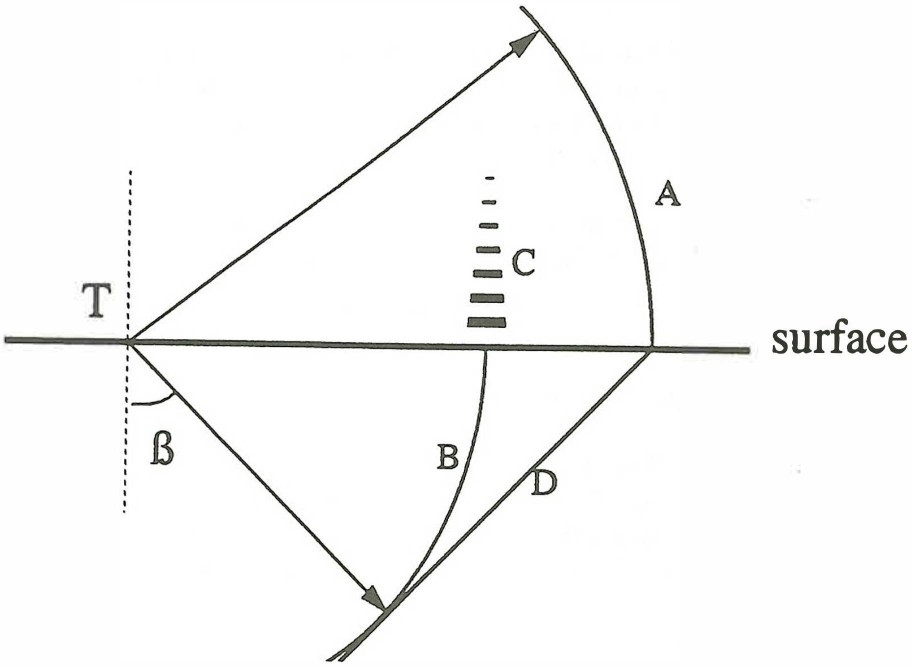

Fig. 1: Wavefronts near a dipole source over the surface (from Annan, A. P. 1973)

The relationship between travel time and the antenna separation for GPR waves is shown in Fig. 2. As is seen, the ground wave appears as a straight line in the CMP (Common Mid Point) recording, and can be easily distinguished from the other waves. However, due to the interference with the air wave and reflected wave, the ground wave can be only observed within a limited distance range.

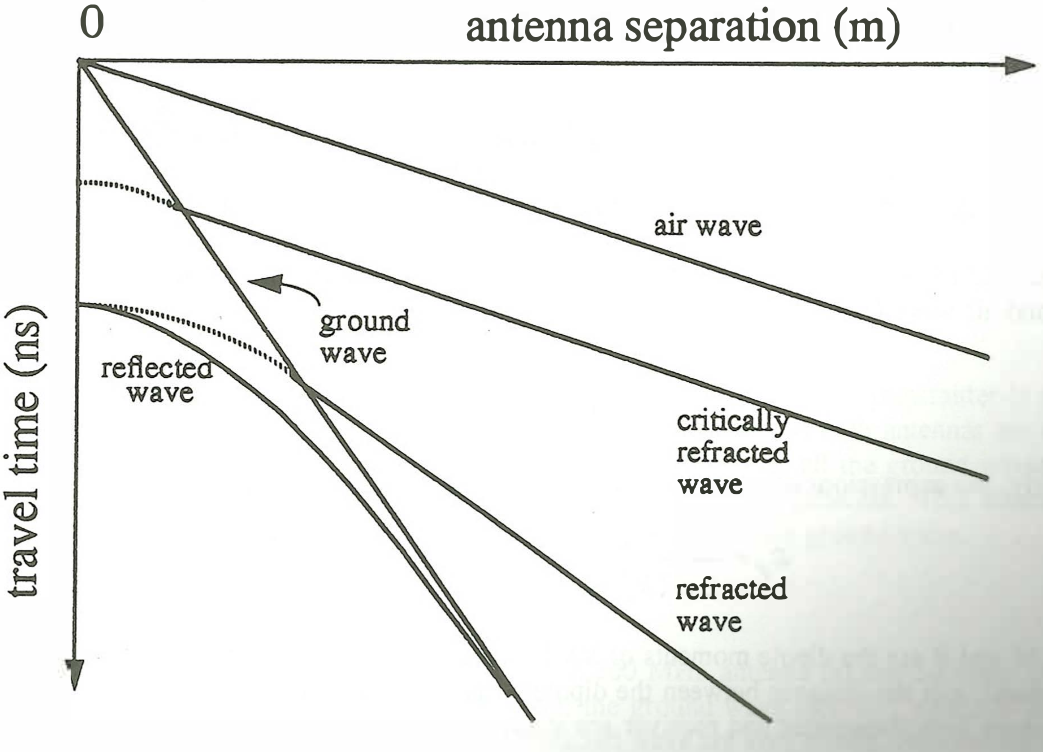

Fig. 2: Travel time dependence of the GPR waves in a CMP recording (comparing with Fig. 4)

## 3 The Wave Nature of the Ground Wave

To discuss the refraction and reflection of the spherical waves from a dipole source, one has to introduce the inhomogeneous plane wave, which refers to a plane wave propagating in a direction given by the wave vector **k**, but whose amplitude falls off in the perpendicular direction. This occurs when the angle of incident is complex (Brekhovskikh, 1960).

Upon refraction at an interface, an inhomogeneous plane wave can be transformed into an ordinary homogeneous wave, and vice versa. This is rather evident from the law of refraction

$$n \sin\theta_1 = \sin\theta_0 \tag{1}$$

where n is the index of refraction, $\theta$ is the angle of incidence and $\theta_1$ is the angle of refraction.

If $n < 1$ and $\sin\theta > n$, then it follows from equation (1) that $\sin\theta_1 > 1$, i.e. $\theta_1$ is complex, and thus the refracted wave is inhomogeneous. This is a well known occurrence and is realized in the case of the total internal reflection waves, where the lateral wave (refracted wave) propagates along the surface, but attenuates exponentially with the distance relative to the surface increasing.

If, in contradiction, $\sin\theta > 1$, i.e. the incident wave is inhomogeneous, but $\sin\theta < n$ (in this case $n < 1$), then we get $\sin\theta_1 < 1$, i.e. the refracted wave will be of the ordinary homogeneous type.

The spherical wave from a dipole placed at a surface can be usually expanded into a sum of plane waves, including inhomogeneous plane waves. Upon refraction into the lower medium, one of these inhomogeneous waves, with wave vector components $k_z = ik(n^2-1)^{1/2}$, $k_x = kn$, is transformed into an ordinary plane wave propagating along the boundary with wave vector components $k_x = kn$, $k_z = 0$. It is just this ordinary plane wave that gives rise to the ground wave.

## 4 The Characteristics of the Ground Wave

The problems concerning the fields of various point dipole sources placed on the surface of a layered earth are widely discussed by Wait (1970), Budden (1961), Brekhovskikh (1960) and others. Although the various solutions for horizontal electric dipole (HED) and vertical magnetic dipole (VMD) sources appear in the literature, a systematic study of the ground wave behaviour does not exist.

By means of the saddle-point method (Brekhovskikh, 1960), the expression of the ground wave and air wave from a VMD can deduced as below

$$H_z = \frac{iM}{2\pi(k_1^2 - k_0^2)} \frac{1}{\rho^2} \left(k_0^3 e^{ik_0\rho} - k_1^3 e^{ik_1\rho}\right) \tag{2}$$

Similarly, the expressions of the ground and air wave for a HED

$$E_y = \frac{i\omega\mu_0 P}{2\pi(k_1^2 - k_0^2)} \frac{1}{\rho^2} \left(k_0 e^{ik_0\rho} - k_1 e^{ik_1\rho}\right) \tag{3}$$

where **M** and **P** are the dipole moments of VMD and HED; $k_0$ and $k_1$ are the wavenumber in the air and ground; $\rho$ is the distance between the dipole source and the point of observation. In the case of GPR where both transmitter and receiver are at the surface, $\rho$ is equal to the antennaseparation $r_x$.

The first and second term in these expressions correspond to the air wave and ground wave respectively.

For comparison, the equation for the reflected spherical wave of a HED is given below

$$E_y = \frac{i\omega\mu_0 P}{4\pi}\frac{1}{r}\frac{\cos\theta_0-\sqrt{n^2-\sin^2\theta_0}}{\cos\theta_0+\sqrt{n^2-\sin^2\theta_0}}e^{ik_1\rho} \tag{4}$$

where $r=(\rho^2+h^2)^{0.5}$; n is the index of refraction; and $\theta_0$ is the angle of incident.

From the expressions above we can deduce some significant characteristics of the ground wave.

The ground wave decays faster (as $1/\rho^2$) with the distance than the reflected spherical wave (as $1/\rho$). This means that the ground wave exists only within a limited distance.

The ground wave attenuates exponentially with the height h above the earth surface. Therefore, the receiving antenna should be placed as close as possible to the surface.

Due to the conductive loss in the earth, the ground wave experiences additional exponential attenuation. As a result, it is more difficult to measure the ground wave in a highly conductive earth.

The amplitude ratio of the ground wave to the air wave increases with the relative permittivity in the earth as $(\epsilon_1/\epsilon_0)^{1/2}$ (from Eq. 2). This makes it easier to measure the ground wave in a moist earth than in a dry one. However, the moisture may also increase the conductivity in the earth.

The last but not the least point concerns the difference of the ground waves between HED and VMD. The relative amplitude of the ground wave to air wave in a VMD seems to be much stronger than that in a HED. Since the air wave appears as the main interference in the measurement, the ground wave in VMD should be more easily determined than in HED.

## 5 Field Experiments

Field experiments were made in different site conditions using CMP mode to find out the influence of factors such as antenna configuration, moisture, antenna frequency and so on. The system used in the field measurements was pulse EKKO IV, manufactured by Sensors & Software Inc., with the antennas of 50 and 200 MHz. The results are summerized as below.

### Moisture

Fig. 3 shows three CMP measurements made near a gravel road. In case (b) transmitter is placed outside the road (grass) while receiver is on the road (gravel). In case (a) both antennas are on the grass, and in case (c) both on gravel. As it is seen from the radargram, all the ground waves have the same propagation velocity, but the relative amplitudes are much different. This means that moisture near the surface influences the amplitude but not velocity of the ground wave.

### Frequency

Figure 4 illustrates two CMP measurements made with 200 MHz antenna (a) and 50 MHz (b) in a farmland As we see, in contrast to 50 MHz antenna, the ground wave recorded with 200 MHz is much weaker, but the reflected wave and critically refracted wave are very strong. As a consequence, the determination of the ground wave with a high frequency antenna is more difficult than with a low frequency antenna.

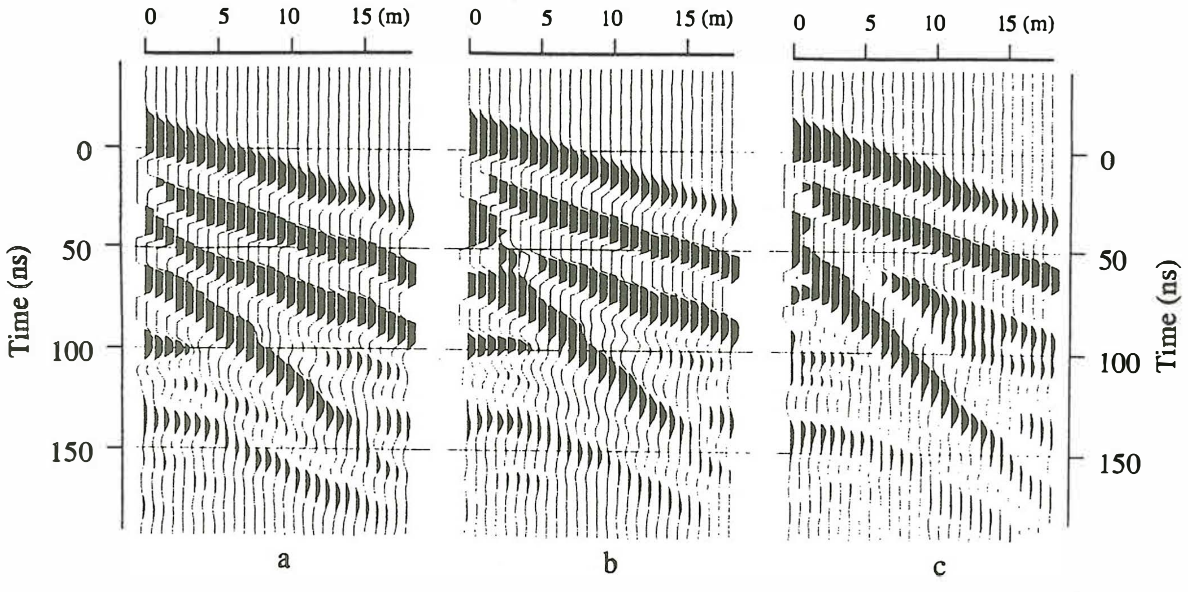

Fig.3: Influence of the moisture on the ground wave

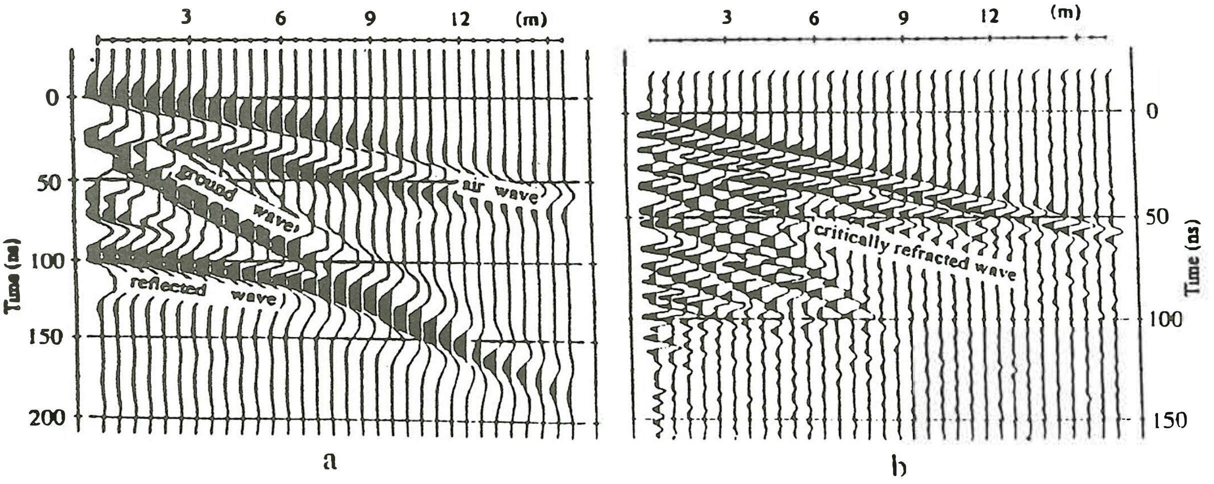

Fig.4: Influence of the frequency on ground wave

## Configuration

The configuration of the antennas also influences the ground wave. From the three possible antenna configurations, the endfire configuration gives the best result (Fig. 5b), and the cross configuration (Fig. 5c) leads to the weakest ground wave, following the broadwide configuration (Fig. 5a).

In contrast to the CMP made with 50 MHz antenna, the results accquired with 200 MHz antenna seem to be very different (Fig. 6). The ground wave is more clear in the broadwide configuration than in the endfire configuration. In fact, wether the ground wave can be identified in the radargram or not, is dependent on its relative amplitude in reference to that of the other waves. In the endfire mode, although the amplitude of the ground wave increases, the critically refracted wave becomes stronger at the same time. Since the influence of the critically refracted wave is usually much more severe with higher frequency antenna, the identification of the ground wave becomes more difficult.

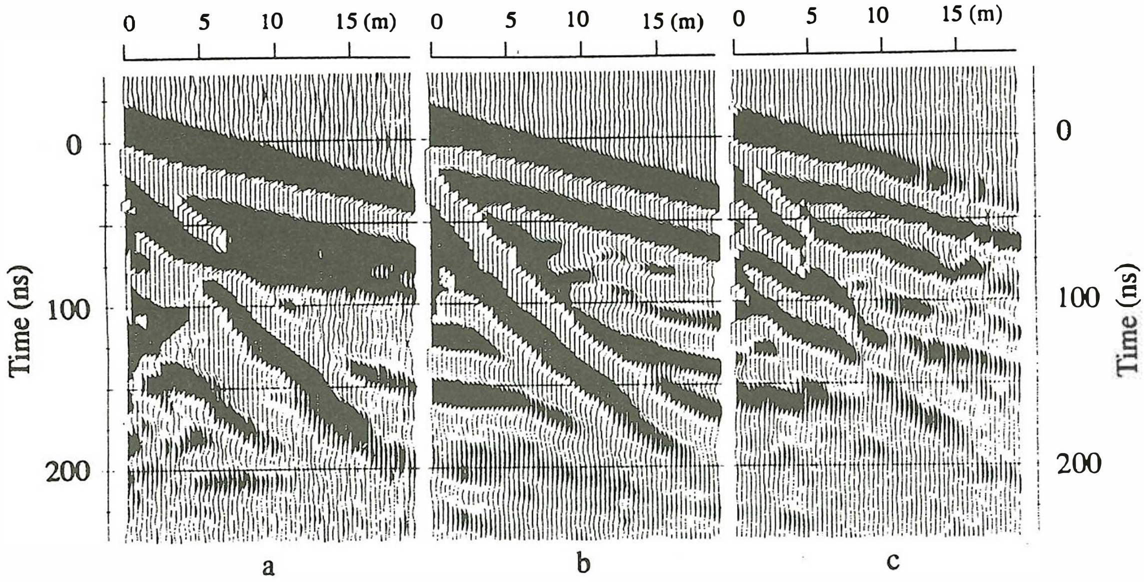

Fig. 5: Influence of the antenna configuration (50 MHz)
a. broadwide b. endfire c. cross

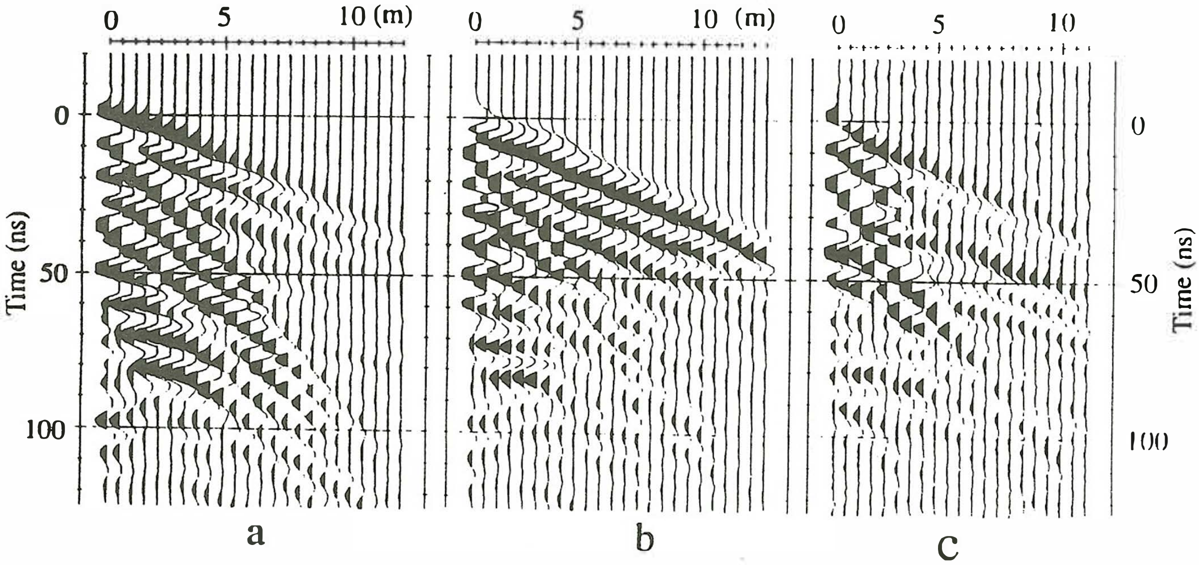

Fig. 6: Influence of the antenna configuration (200 MHz)
a. broadside b. endfire c. cross

Theoretically, the amplitude of the ground wave decreases with the height of the antenna above the surface. However, if the antenna is not elavated much from the earth surface, this influence seems not to be a severe problem. Fig. 7 illustrates a test about such an effect. The transmitter and receiver are lifted up to 5 and 15 cm, but there is only a small variation in the amplitude of the ground wave.

## 6 Information Depth of the Ground Wave

As discussed earlier, the ground wave results from the spherical wave when refracted at the surface. It follows from this that the information depth (i.e. the where the most information comes from) of the ground wave is mainly determined by its wavelength λ in the earth

$$\lambda = c/\left(f\sqrt{\varepsilon_r}\right) \qquad (5)$$

where $\epsilon_r$ is the relative permittivity in the subsurface.

In other words, the information depth of the ground wave decreases with the antenna frequency and the soil water content in the subsurface.

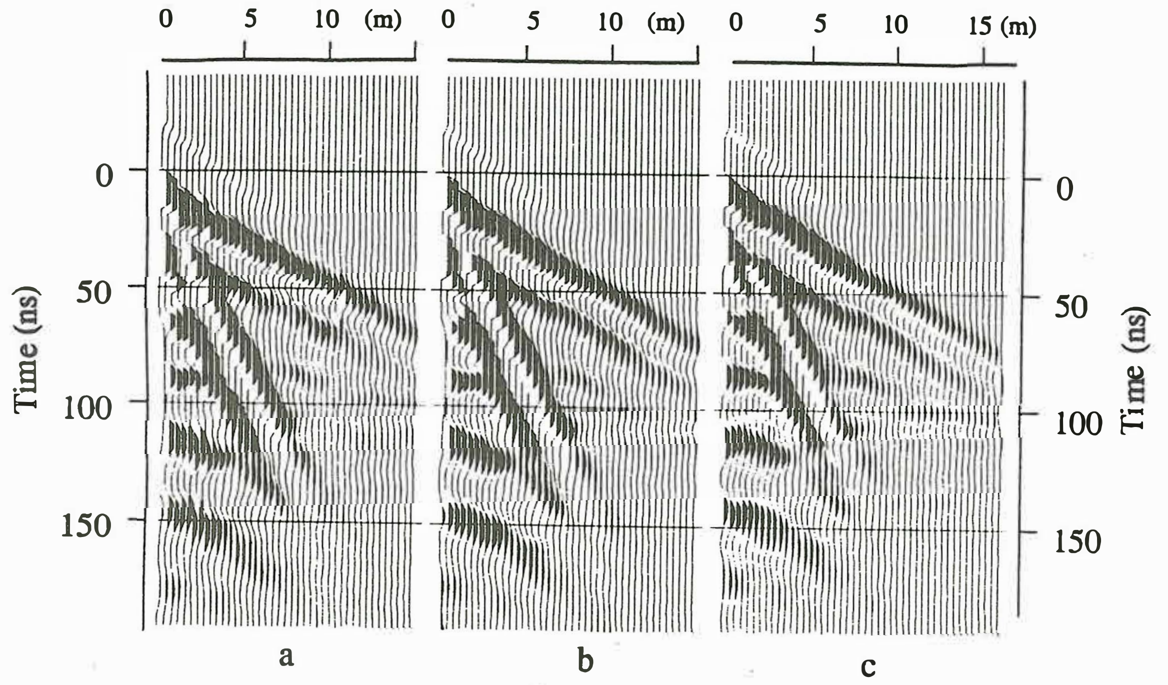

Fig. 7: Influence of the height of the antenna (h) above the surface
a. h=0 cm b. h=5 cm c. h=15 cm

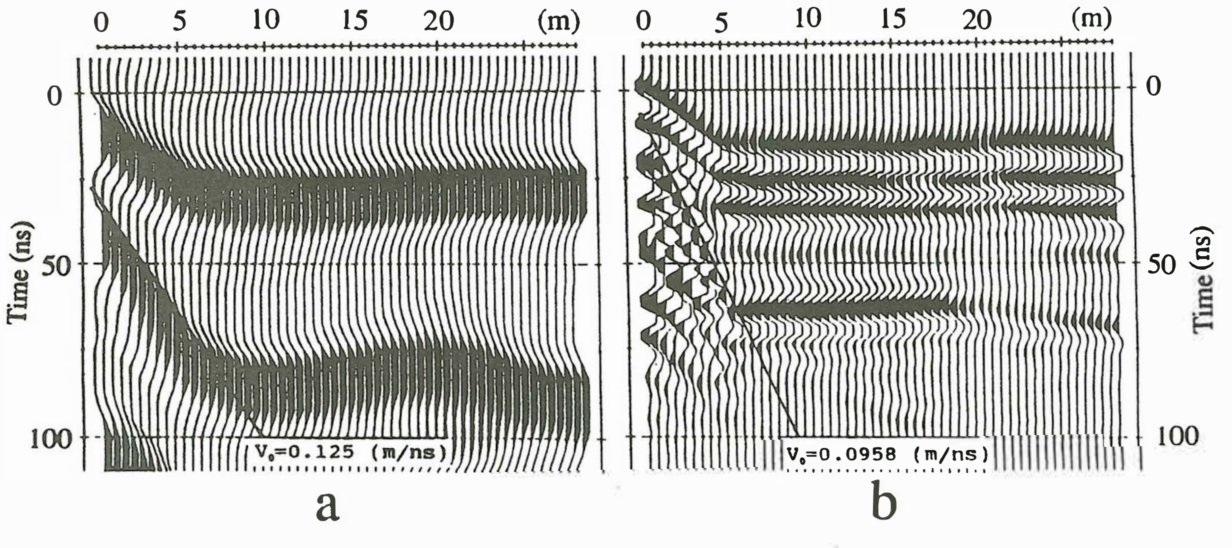

Fig. 8: CMP measurements made with 50 MHz (a) and 200 MHz (b) antennas.

Figure 8 shows a profile measurement in a grassland with different antenna frequencies. As we see, the velocity of the ground wave measured with 200 MHz is much lower than that with 50 MHz. Both profiles are measured with the same antenna separation but show different horizontal variation of the arrival time of the ground wave, since the water content in the grassland decreased with the depth. So the distinction of the velocity of the ground wave may be attributed to the different information depth of the two antenna.

Another measurement was made over ice with a 50 MHz antenna. As it is seen from the radargram (Fig. 9), the ground wave propagates with a velocity of 0.037 m/ns, far smaller than the expected propagation velocity in ice (0.16 m/ns). This may be explained as follows: the wavelength of the ground wave in ice is about 3 meters for the 50 MHz antenna. Since the ice sheet has a thickness of about 15 cm, the ground wave propagates mainly beneath the ice (in the water). In other words, the velocity of the ground wave in this case is determined by the water. In fact, the measured value 0.037 m/ns rather approximates the velocity of GPR wave in water (0.033 m/ns).

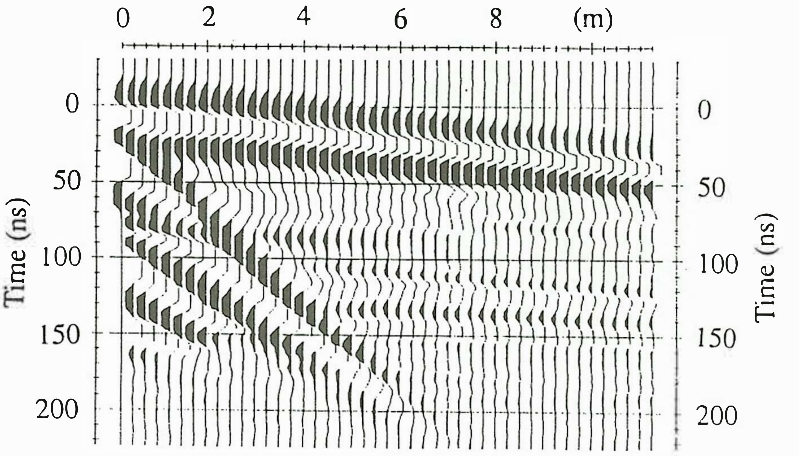

Fig. 9: CMP recording made on an ice sheet

## 7 Conclusion

The ground wave is in fact a kind of ordinary plane wave which propagates horizontally along the surface. Its information depth depends on the wavelength, i.e. on the water content in media and the frequency of the antenna. Many factors may influence the amplitude of the ground wave. In addition to the moisture near the surface, the antenna configuration and antenna frequency are the most important factors to be considered for measuring the ground wave.

## 8 Acknowledgements

The authors would like to express their gratitude to the company Geolog in Starnberg for the generous technical support.

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