GPR and Its Application to Environmental Study

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Preface:

This text is prepared for a seminar to be held at Mongolian Technical University, Ulaanbaatar, Mongolia in January 2001 by Motoyuki Sato, Tohoku University, Japan.

This two-day seminar will be held to introduce the Ground Penetrating Radar (GPR) technology to potential users and researchers in Mongolia. GPR has been widely accepted in many subsurface applications. They include Geology, Geophysics, Hydro-geology, Archaeology, Civil Engineering. In August 1999 and September 2000, we tested GPR in Ulaanbaatar area and could show some good results. Especially its capability of detecting ground water is remarkable. In this seminar, I would like to introduce the fundamental technology of GPR to actual applications I various fields. Finally, I would like to discuss with many researchers in Ulaanbaatar about the future possibility of usage of GPR in Mongolia.

GPR technology is closely related to Electromagnetic wave theory and signal processing technology. Therefore, I believe this seminar is also very useful for researchers and students who are studying electrical communications and signal processing theory. I will bring processing software, which works, on Windows95/98, and some Radar data acquired in Ulaanbaatar. These practical examples will be very useful for these researchers, post-graduate students, graduate students and undergraduate students.

I acknowledge greatly for the help of my colleagues in Mongolia and Japan for supporting this seminar. Especially I thank Prof. O.Gerel, Director of Geoscience Center of Mongolian Technical University. She stayed at my laboratory as a visiting professor for 4 months in 1997. This is the initiation of our collaborative study in Mongolia. I also acknowledge Dr. D. Badarch, Rector of Mongolian Technical University. He strongly supported our research activities. It is my great pleasure that the Geoscinec Center of MTU and CNEAS Tohoku University have agreed academic exchange program in 2000. In 2001, the university academic exchange program will be officially begin between Tohoku University and Mongolian Technical University. I hope this seminar will promote further collaboration of Japanese and Mongolian scientists in science and technology for environmental study and other applications.

Introduction

We introduce a use of Ground Penetrating Radar (GPR) to survey of ground water for environment study in Mongolia. GPR is a geophysical exploration technique, which has an advantage in a compact equipment and fast data acquisition. This technique is highly sensitive to water content in soil, therefore, we think GPR is very suitable for environment study in Mongolia.

Ground penetrating radar (GPR) has been extensively applied to investigate subsurface structures or buried objects in geology, civil engineering, environment and soil science. This non-destructive method of subsurface analysis is becoming increasingly important for many environmental and shallow geophysical applications. GPR can quickly and accurately determine the subsurface structure. The GPR equipment can easily move on the ground surface, so it is suitable for survey in vast area.

Generally, GPR is able to map subsurface structure at depths from a few tens of centimeters to five meters. The detectable range of GPR survey is depends on soil and sediment mineralogy, clay content, but the most important factor is the water content in the soil. Generally, electromagnetic wave can easily penetrate into dry soil, therefore GPR can easily be applied to dry regions like Mongolia. On the other hand, the attenuation of electromagnetic wave in ice or frozen soil is also low. Therefore, GPR technique is suitable in cold region like Siberia, too.
The advantages of GPR survey are listed below:

1. Fast Data Acquisition
2. On-site Mapping
3. Detection of Metallic and Nonmetallic Objects
4. Wide Application
5. High Sensitivity to Water

Generally, GPR has been accepted in application areas such as ground water detection, detection of water path I crystalline rocks, geological survey. Especially in dense are such Japan, geo-technical applications such as buried pipe detection, detection of void under pavement, concrete monitoring are quite active. These technologies should also be introduced to Mongolia. Quite recently, applications to archaeological survey, environmental study and UXO or manmade mine detection also gather interest in the world.
Borehole radar is also very unique and important technique, but it will not be discussed in this seminar.

2 GPR Principle

2.1 Electromagnetic Wave Propagation in Subsurface Material

The electromagnetic wave in subsurface material is governed by Maxwell's equation. The electromagnetic wave behavior in subsurface material is strongly dependent on its electrical conductivity. And the electrical conductivity is normally controlled by water. When material conductive, electromagnetic filed is diffusive and cannot propagate as electromagnetic wave. When it is resistive, or dielectric, electromagnetic field can propagate as electromagnetic wave. Some electromagnetic geophysical exploration methods such as MT and EM methods use the EM diffusive filed, because the penetration depth is large. However, the interpretation is not easy in these methods. GPR use the EM wave and its interpretation is rather easy. The material characteristics vary from diffusive to dielectric, when we change the frequency. This is normally described by the tangent loss factor or $\tan\delta$. Eq.(2.1) is the Ampere's Law in EM field. The ratio of the conducting current to the displacement current defines the $\tan\delta$ as shown in Eq.(2.2).

$$\nabla\times\mathbf{H}=\sigma\mathbf{E}+j\omega\varepsilon\mathbf{E} \qquad (2.1)$$

$$\tan\delta=\frac{|\sigma\mathbf{E}|}{j\omega\varepsilon\mathbf{E}}=\frac{ConductingCurrent}{DisplacementCurrent}=\frac{\sigma}{\omega\varepsilon} \qquad (2.2)$$

When we use higher frequencies, all the material behaves as dielectric because the displacement current dominates the conducting current, and the EM field propagates as wave, although the attenuation is generally high. This situation is graphically shown in Fig.2.1.
All the electrical characteristics of material is determined by electrical conductivity, permittivity and permeability. In GPR technology, the permittivity is the most important parameter, because in higher frequency

any material behaves as dielectric.

GPR measures the reflected electromagnetic wave from subsurface structure. The velocity and reflectivity of the electromagnetic wave in soil is characterized by the dielectric constant (permittivity) of the soil. When the dielectric constant of the soil is ε_r, the velocity in this material is given by

$$v = \frac{c}{\sqrt{\varepsilon_r}} = \frac{3\times10^8}{\sqrt{\varepsilon_r}}(m/s) \qquad (2.1)$$

The wavelength λ (m) and the operating frequency *f*(Hz) and the velocity of the wave is related as:

$$\lambda = vT = \frac{v}{f}(m) \qquad (2.2)$$

Eq. (2.2) shows that the wavelength and frequency are in inverse proportion.

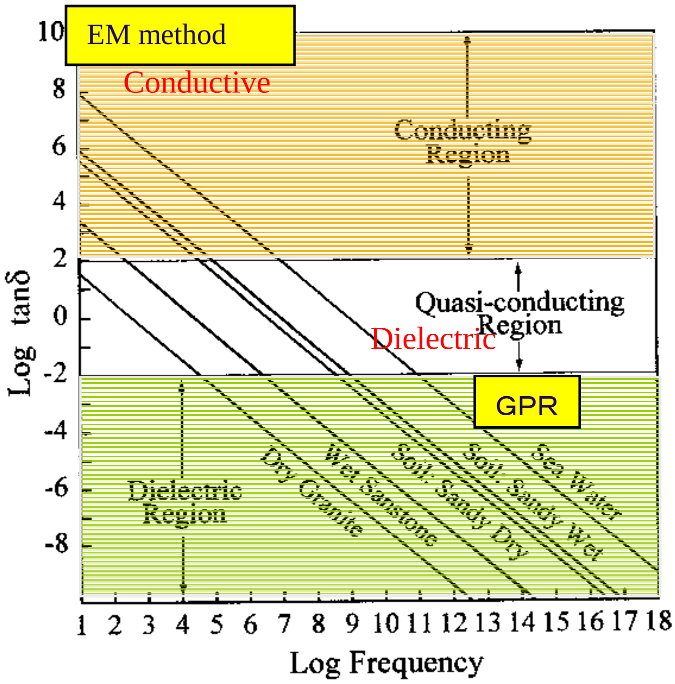


図7.1　地下構成物質の誘電正接と周波数の関係

Fig. 2.1 Frequency Dependency of Subsurface Material

2.2 Reflection of Electromagnetic Wave

GPR transmits a pulsed electromagnetic wave from a transmitter located on the grounds surface and signals are received by a receiving antenna on the ground surface. The transmitted signal propagates through the subsurface material and reflected by objects such as geological boundary, buried objects and ground water. The received signal is recorded by a Personal Computer (PC). When the electromagnetic wave velocity v is known, measuring the travel time τ (s), we can estimate the depth of the reflecting object d(m) as follows:

$$d = \frac{v\tau}{2}(m) \qquad (2.3)$$

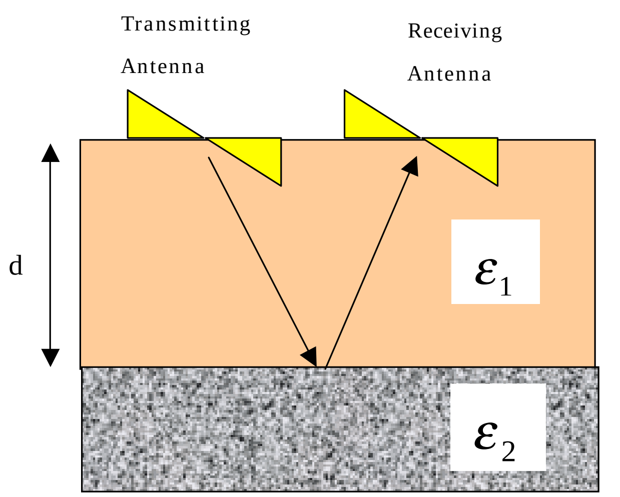


Fig. 2.2 EM wave reflection at a geological boundary

The travel time is defined as a time from the timing of the transmitted signal and the timing of the received signal, which correspond to the propagation time to the reflecting object.

The reflection occurs, when the EM wave encounters any electrically inhomogeneous material. The most significant electrically inhomogeneous material is metal. Any buried metallic material such as pipes and cables are quite easy for detecting by GPR. However, it is very important that even a insulating material can be electrically inhomogeneous material. Insulating material is referred as dielectric material. And its characteristics is defined by the dielectric constant. The dielectric constant is also called permittivity. Any material having two different dielectric constant causes EM wave reflection.

When electromagnetic wave is incident to a flat boundary of two different materials having the dielectric constant of ε_1 and ε_2, the EM wave having the amplitude of 1 is reflected by the boundary and its amplitude is Γ. Γ is defined as a reflection coefficient of a boundary and is given by

$$\Gamma = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \qquad (2.4)$$

Eq. (2.4) shows that the amplitude of the reflected wave is defined by the ratio of the dielectric constant of the two material. The reflection coefficient Γ takes value between $-1 \le \Gamma \le 1$. If the lower material is metal, the reflection coefficient is

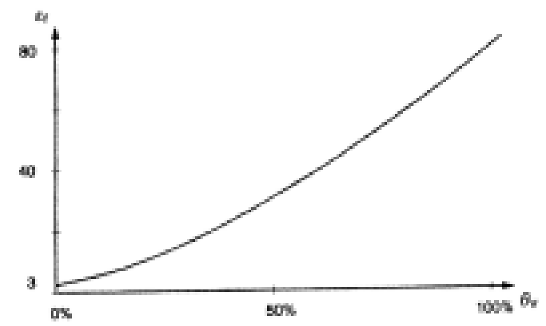
$$\Gamma = -1 \qquad (2.5)$$

and it takes the maximum amplitude. Therefore, the reflection from metallic material is always very obvious. This condition stands even when the metallic material is a thin sheet, because all the EM energy is reflected by the metallic sheet.

In actual GPR measurement, the radar target is not infinitively large, but it has a finite size. Generally, a larger target reflects stronger signals, when the size of the target is smaller that the wavelength. The GPR wavelength is normally more than 1m, and this condition is valid for most of the GPR targets. In this case, the amplitude of the reflected wave is a good measure of the size of the radar target. This amplitude can normally be related to the RCS (Radar Cross Section).

On the contrary, a linear object such as pipes has a strong dependency of reflectivity of the EM wave polarization. When the direction of the pipe is collinear to the incident EM wave, even the diameter of the pipe is very small compared to the wavelength, the reflectivity is very large. When the incident polarization is perpendicular, a metallic pipe does not reflect EM wave. Therefore, GPR polarization is very important in applications such as pipe and cable detection.

2.3 Dielectric Constant of rock and Geological Material



The dielectric constant of subsurface material consists from rocs and soil varies by the constitution material its selves, however, the dielectric constant of these material have similar value, and the water contained in the material is most significant in the dielectric constant. The dielectric constant and the attenuation of typical subsurface ,aterial is summarized in Table 2.1. Fig.2.3 shows the typical relation ship between the water content of soil and water content in the soil. From Eq.(2.4), we can understand any change of water condition in the soil and geological formations can cause the EM reflection.

Fig.2.3 The typical relative permittivity and water content of soil

We can assume two different conditions which cause the difference of the water content in actual geological formations. The first is the same geological material having a different water content. The second is two different materials having different water contents. The former is used for GPR monitoring of water irrigation for agriculture, detection of ground water level and ground water penetration and monitoring of grouting. The dielectric constant of the rock and soil material in dried condition have the value between 3 and 5 and their contrasts are not so large. However, its water content can be changed quite largely, causing a large contrast of dielectric constant. Therefore, detection of geological boundary by GPR is normally very effective, when the geological material has even very small water content. Even when two materials are consists from the same material, if the compression is different is different in two materials, the water content can be changed. This condition is often found in archaeological survey. In this situation, we find archaeological or artificial geological boundary, where the soil is very strongly compressed, and it contains less water than the surrounding material, which causes strong EM reflection.

Table 2.1 Attenuation and relative permittivity of subsurface material measured at 100MHz (Daniels, 1996)

Material	Attenuation (dB/m)	Relative permittivity ε_r
Air	0	1
Asphalt: dry	2-15	2-4
Asphalt: wet	2-20	6-12
Clay	10-100	2-40
Coal: dry	1-10	3.5-9
Coal: wet	2-20	8-25
Concrete: dry	2-12	4-10
Concrete: wet	10-25	10-20
Fresh water	0.1	80
Fresh water ice	0.1-2	4
Granite: dry	0.5-3	5
Granite: wet	2-5	7
Lime stone: dry	0.5-10	7
Lime stone: wet	10-25	8
Permafrost	0.1-5	4-8
Rock Salt: dry	0.01-1	4-7
Sand: dry	0.01-1	4-6
Sand: saturated	0.03-0.3	10-30
Sandstone: dry	2-10	2-3
Sandstone: wet	10-20	5-10
Seawater	1000	81
Seawater ice	10-30	4-8
Shale: saturated	10-100	6-9
Soil: firm	0.1-2	8-12
Soil: sandy dry	0.1-2	4-6
Soil: sandy wet	1-5	15-30
Soil: loamy dry	0.5-3	4-6
Soil: loamy wet	1-6	10-20
Soil: clayey dry	0.3-3	4-6
Soil: Clayey wet	5-30	10-15

3 GPR Survey

3.1 GPR system

Evaluation of the GPR system performance

The performance of a radar system can be evaluated by two important factors, namely maximum detectable range and radar resolution. The maximum detectable range is defined by the maximum distance, which the radar can detect the object, the radar resolution is defined as the minimum distance between two different objects which are located close to each other.

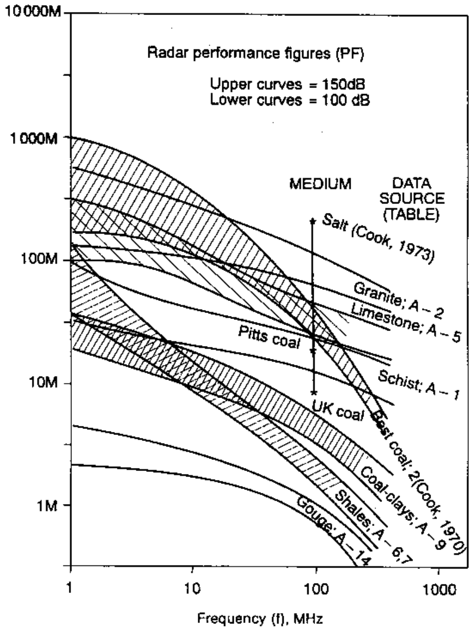


図7.7　典型的な地中媒質に対するレーダ探査距離
(Cook, 1975)

Fig.3.1 GPR system performance and the maximum detectable range

The maximum detectable range, which is the maximum detectable depth in GPR, is determined by the ratio of the transmitted power and the minimum detectable signal level, which is normally the noise revel of the receiver. The detectable range in a free space is determined by the radar equation, but for GPR, the detectable depth is strongly dependent on the subsurface material. Therefore, this ratio is called the system performance of a GPR system and used as an indicator of the maximum detectable depth. Typical GPR systems have the performance factor between 100-150dB. Fig. 3.1 shows the corresponding maximum detectable range in some subsurface materials.

The EM wave propagating through subsurface material is suffered from a strong attenuation. The attenuation is dependent on the frequency, and higher frequencies normally have higher attenuation. Therefore, even in the same material, if we use a higher frequency in GPR, the maximum detectable depth decreases. On the contrary, the radar resolution is related to the wavelength. Three pipes are separately recognized in Fig.2.4, so the radar resolution is higher than the separation of the pipes, and in this particular case, it is better than 1m. If we use longer wavelength for GPR measurement, the scattered wave from each pipe will be superimposed and they cannot be discriminated from each other. Summarizing the parameters governing the radar characteristics can be described as follows:

Frequency	Low	―	High
Wavelength	Long	―	Short
Attenuation	Large	―	Small
Radar Resolution	High	―	Poor
Maximum Detectable Depth	Deep	―	Shallow

Since the radar resolution and the maximum detectable depth is completely opposing factors as for frequency, the selection of the operating frequency is the most important design factor in GPR. The most GPR systems are working at 50MHz to 1Ghz.

Radar Modulation

The EM wave from a GPR system is radiated to relatively wide angle, and many reflections from different directions are received by a receiving antenna fixed at one position. The GPR receiving signal is measured in the time-domain and each reflection signal is discriminated by the different arriving times. A signal waveform containing two reflected signals can be represented in the time domain as Eq.(3.1) and is transformed into the frequency domain as Eq.(3.2) by Fourier transformation. By the definition of the Fourier transformation, both signals have the equivalent information.

$$f(t) = A_1\delta(t-\tau_1) + A_2\delta(t-\tau_2) \qquad (3.1)$$

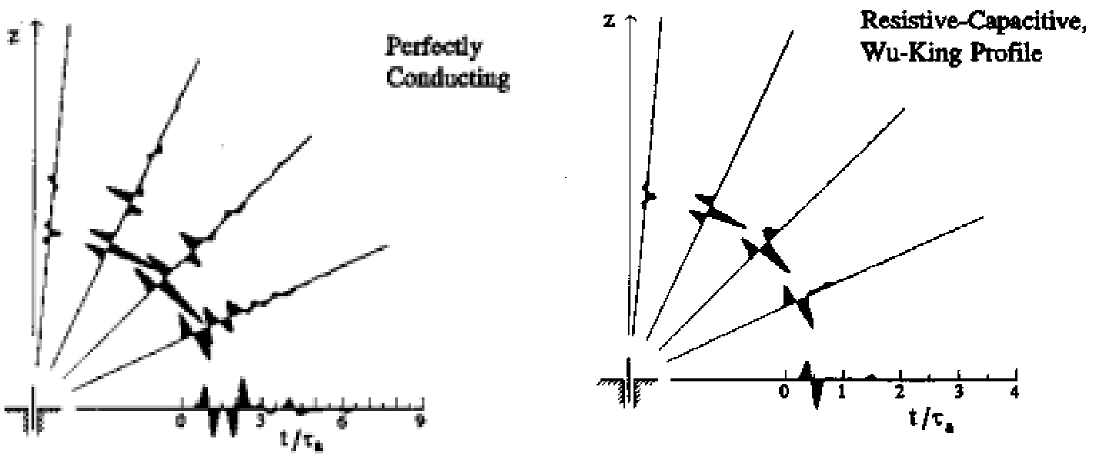
$$F(\omega) = A_1 e^{-j\omega\tau_1} + A_2 e^{-j\omega\tau 2} \qquad (3.2)$$

However, Eqs(3.1) and (3.2) are equivalent only when they are acquired $-\infty < t < \infty$ in the time domain and $-\infty < \omega < \infty$ in the frequency domain. The finite length of the measured signal or the limited frequency bandwidth can violate this condition. Also, signal is not a practical definition. Also the signal to Noise ratio (SNR) can be differed by the way of the data acquisition and it determines the characteristics of the radar system.
The most commercial GPR system uses an impulse, which is exactly speaking a very short impulse less than 1ns, as a transmitting signal and receive signal in the time domain. This type of radar system is called a impulse radar system.

On the contrary, some special types of radar systems transmit a continuous sinusoidal wave, which is called continuous wave (CW) radar system.

GPR Antenna

Dipole antennas and its deformed antennas are normally used in the transmitter and the receiver in GPR systems. A dipole antenna consists from a pair of insulated metallic elements, which are normally conducting rods, called antenna elements. High frequency voltage is applied across the gap between the two conductors, initiating high frequency current flowing along the elements. This current radiates the EM wave into the field. When the EM wave is incident on the antenna element, the EM wave induce the current on the antenna and induces the receiving voltage across the elements. Both in transmission and reception, the current flowing along the antenna elements play important roles. In the transmission, the current on the element radiate EM wave and the energy in the current is reduced, however, the remaining current is reflected at the apex of the antenna element. This current continues to flow along the element until all the energy is radiated. The velocity of the current on the antenna is fixed, and the periodic reflection causes antenna resonance.



(a)Conducting antenna element (b)Resistively loaded antenna element

Fig.3.2 Transient EM field radiated from a pulse excited dipole antenna (Montoya & Smith, 1996)

When a single frequency is used, half wavelength dipole antenna causes a strong resonance and is used for an effective radiator. In most communication and broadcasting systems, this type of antenna resonance is used in antennas. Therefore, a half wavelength dipole antenna is one of the most widely used antennas. However, a short pulse, which contains wide frequency band spectrum is used excitation of an antenna in GPR, most of the transmitting power has the different frequency from the tuned frequency of the half wavelength antenna. Fig.3.1 shows the transient radiated field from a pulse excited dipole antenna. Fig.3.2(a) shows the field from a conducting antenna element. A train of pulsed are radiated to the normal direction. Fig.3.2(b) shows the radiated field from a resistively loaded dipole antenna. The radiated EM wave is consists from a single pulse. In many GPR radar profiles, we observe signals containing periodical signal following a strong reflection signal. This is referred as “ringing” of a radar signal, which shades a small reflection after stronger reflection. The ringing of GPR signal is caused by the resonance of the antennas, and they can e suppressed by an appropriate antenna loading. Most of the commercial GPR system antennas have these resistively loading or Bow-tie antenna, which also reduce the effect of resonance. Fig.3.3 shows an example of actual transmitted signal from a GPR system. This signal has a dominant frequency at 100MHz but the power spectrum is spread between 50MHz and 200MHz. In time domain, significant ringing corresponding to 100MHz is observed.

The transmitted EM wave from an antenna is radiated not only into the subsurface material, but some part of the energy is radiated into the air. The radiated EM wave into air can be serious noise for other radio communication apparatus such as radio, TV and mobile telephone. In order to avoid this undesired radiation., many commercial GPR antennas are covered by an antenna shielding, which is made from a metallic sheet and EM wave absorbing material such as Ferrite. Especially, all the Japanese commercial GPR systems are equipped with a switch, which automatically prevent transmitting EM wave, when the antenna is not facing the ground surface. The antenna shielding is also effective to suppress reflection signal from objects above the ground surface, which are often misunderstood as a subsurface objects.

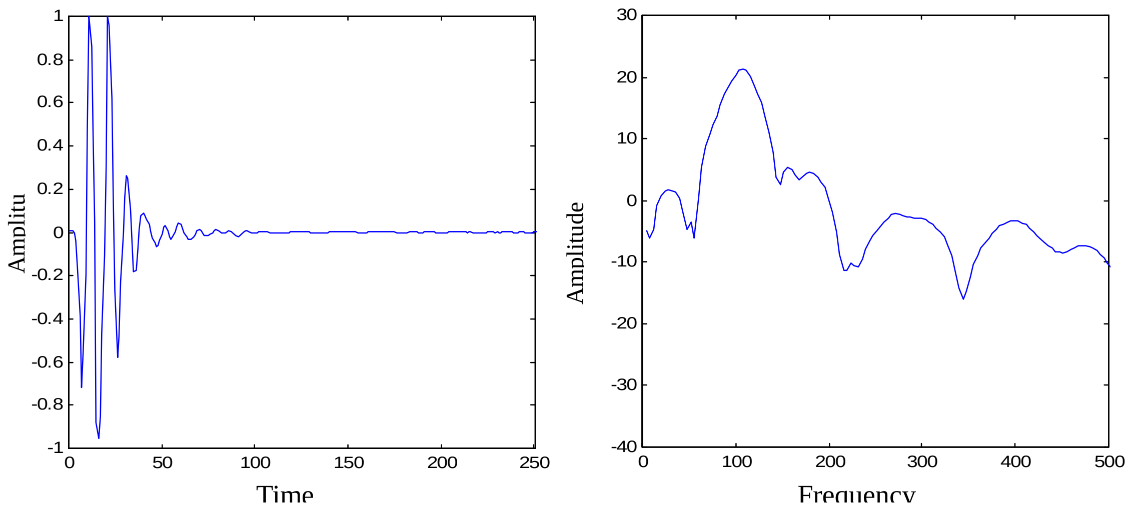


Fig. 3.3 Radiated EM wave in time domain and its power spectrum
(RAMAC GPR 100MHz antenna)

GPR System

Typical GPR system diagram is shown in Fig.3.4. The radar system is composed from a transmitter, a receiver, antennas connected to them, a controlling unit and a signal display with a recording system. All these components are equipped in one unit in some systems, which are often used for pipe and cable detection under pavement. This system can be used only for the profile measurement, which will be described in section 3.2. In other applications such as geological survey needs wide-angle measurement, and for this purpose, GPR systems, which have separated components, are used.

For example, RAMAC GPR system with 200MHz, 500MHz and 1GHz antennas have a unified components, and 50MHz and 100MHz antennas have separated components.

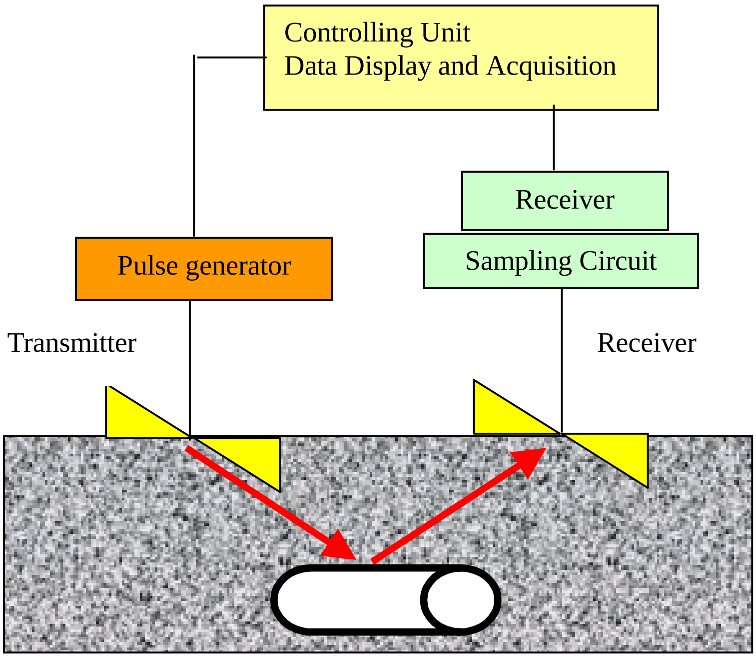


Fig.3.4 GPR System Diagram

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Fig.3.5 GPR system with unified components (KODEN GPR)

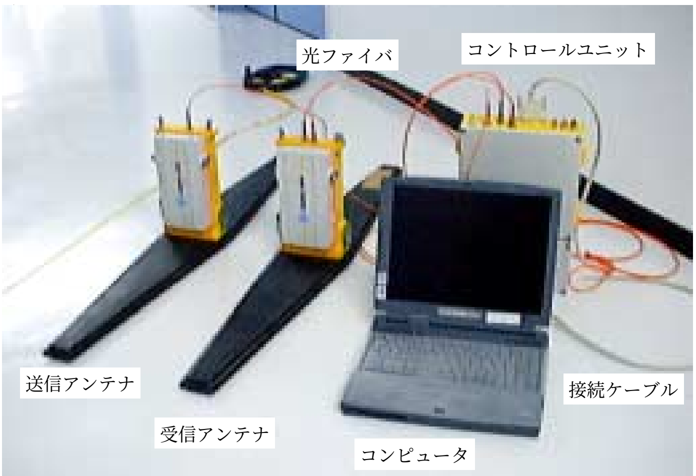


Fig.3.6 GPR system with separated components (RAMAC GPR with the 100MHz Antenna)

3.2 GPR Survey Method

Antenna Arrangement

There are two antenna arrangements in GPR survey. One is the profile-measurement (Common Offset), where the separation of the transmitting antenna and the receiving antenna is fixed, and the both antennas are moved together. The other is the wide-angle –measurement (CMP: Common Offset) , where the separation of the transmitting antenna and the receiving antenna is changed in each data acquisition. In most GPR survey, the common-offset measurement is used, because it is easy and fast. When we need precise measurement or require deeper survey, the wide-angle measurement is used.

In the profile-measurement, we measure the reflection form objects located just below the antennas continuously. This gives us information about the horizontal location of the objects and rough estimate of its depth. In order to determine the depth of the object, we have to know the wave velocity beforehand. However, we cannot get the velocity by the profile-measurement. The data acquisition in the profile-measurement is very fast, and normally we can measure at walking velocity. Sometimes GPR systems are equipped aboard an car or an airplane to acquire data along a very long survey line.

If we need to know the precise depth of the object or detect deeper object that the profile measurement cannot achieve, the wide-angle-measurement is used. In this measurement, we fix the position of the Common Midpoint (CMP) at one location, and move the transmitting antenna and the receiving antenna to an opposite direction keeping the same distance from the CMP. In this antenna arrangement, we measure reflected wave from the same reflecting objects many times. The reflected wave, which is located below the CMP, forms a hyperbolic curve, and we can estimate the depth of the object and the velocity simultaneously. This technique is called NMO correction, which has been widely accepted in seismic signal processing. When we can estimate these two parameters correctly, we can re-locate the reflected wave on the same arriving time as shown in Fig.3.8(c). This process is known as NMO correction. When the estimation of the velocity and the depth is correct, all the traces are aligned horizontally. Then we take the average of the traces. This process is known as a CMP gather. NMO correction and CMP gather is taking a spatial correlation of reflected signals acquired at different antenna positions. In each measurement, noise and clutter from other reflecting objects are incoherent, therefore, we can improve the SNR in the CMP gather.

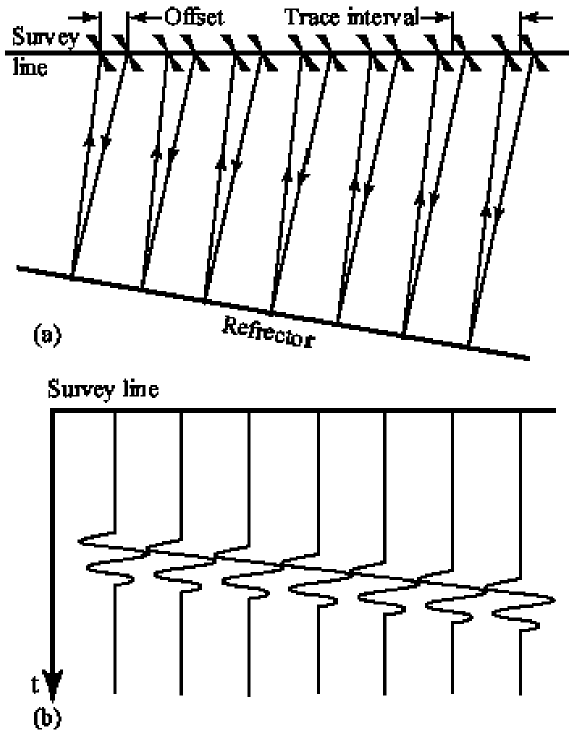


Fig.3.7 Profile measurement
(Common Offset)

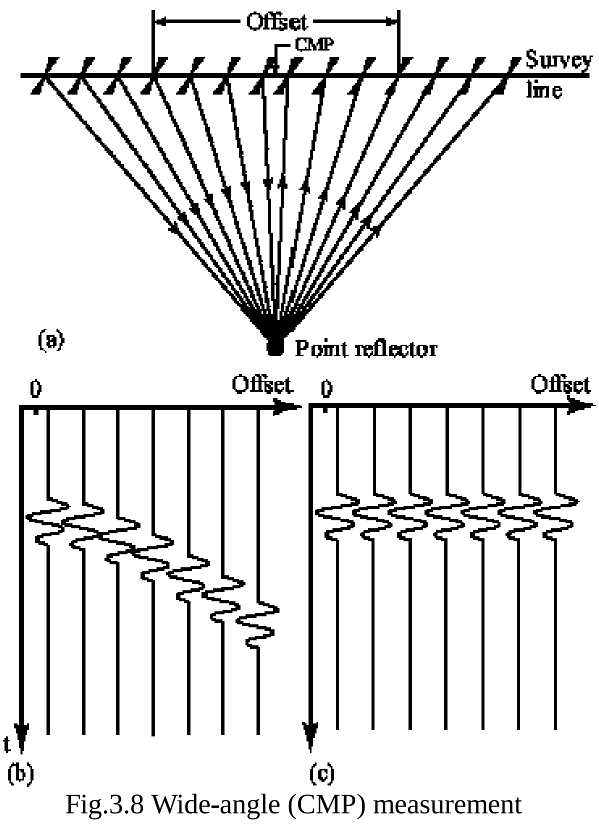


Fig.3.8 Wide-angle (CMP) measurement

Measurement Techniques of the Dielectric Constant

The estimation of the EM velocity is important for interpretation of the GPR profiles. Since GPR measurement cannot directly give the velocity, we have to use additional or other techniques for determination of the velocity as follows:

(1)Analyze reflection wave from a point target in the profile-measurement.
(2) CMP analysis in the wide-angle measurement.
(3)Use TDR apparatus and measure the dielectric constant of the material near the surface.
(4)Laboratory measurement using sample.

TDR（Time Domain Reflect meter）is an apparatus, which measure the water content of the soil by measuring the travel time of an EM pulse reflected by a short parallel rod, which is inserted into soil. TDR directly gives the velocity of the EM wave in soil. The water content can be estimated by Eq.(2.1) and Fig.2.5. TDR apparatus is a very compact as shown in Fog.3.9 and gives a good estimate of the dielectric constant.

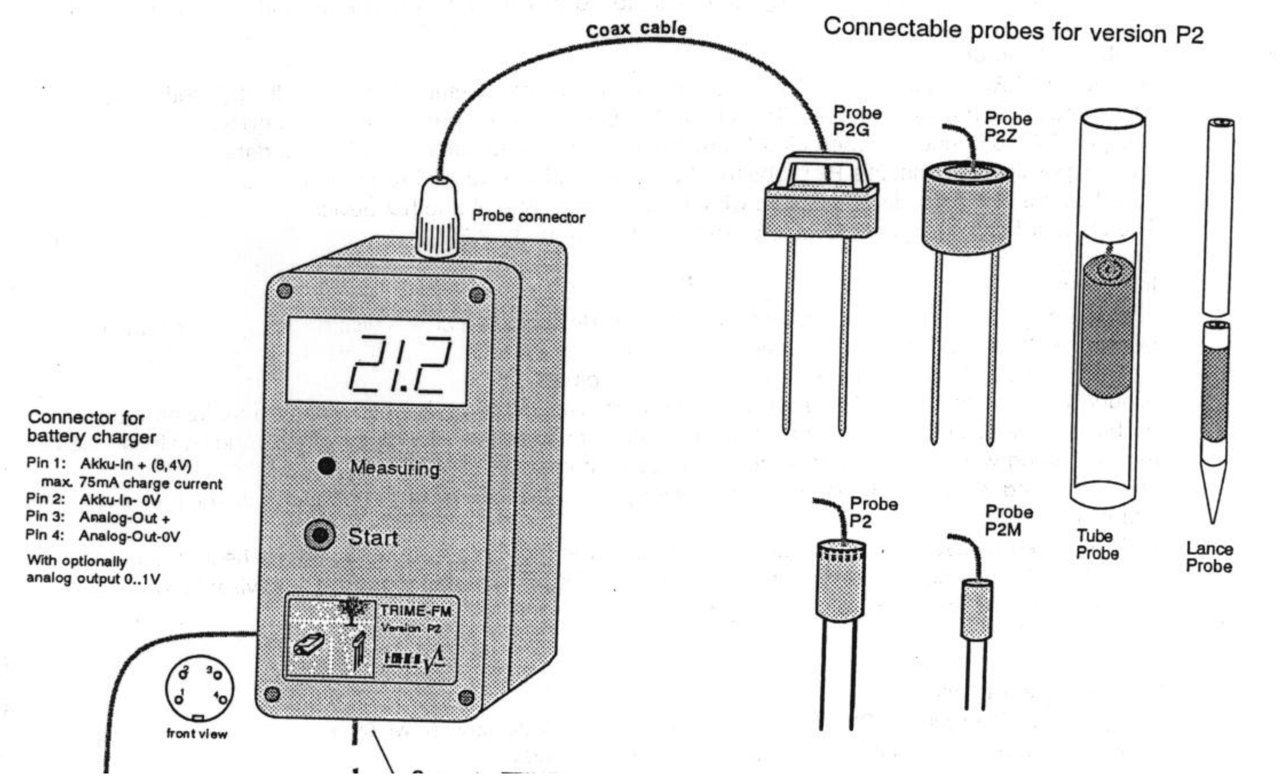


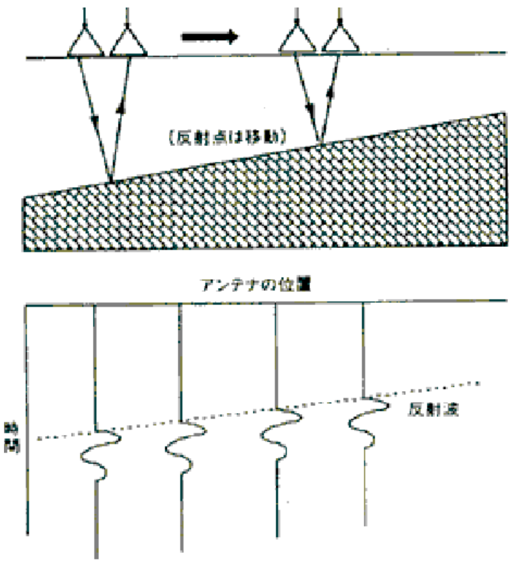
Fig. 3.9 TDR Apparatus (TRIME-FM)

4 GPR Signal Processing

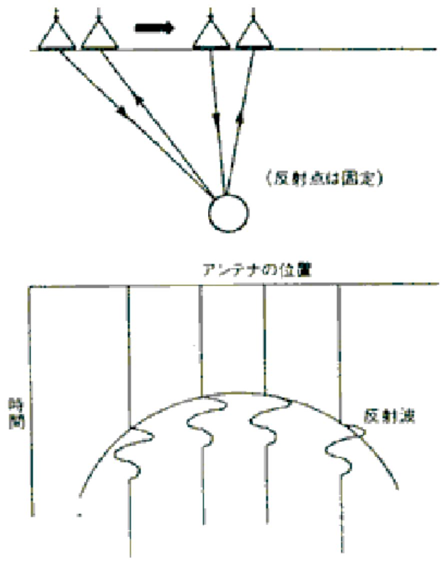
4.1 Subsurface Structure and GPR Profile

In the profile measurement, the transmitting and the receiving antennas are moved together on the ground surface. We can estimate the rough subsurface structure directly from the continuous travel time of the GPR signal as shown in Fig.4.1. However, we have to notice that this GPR profile is not always the true subsurface structure. For example, if we have a point reflector such as a metal pipe, the reflected signal is scattered into wide angle and are measured in wide areas as shown in Fig. 4.1(b). When the object has relatively flat structure, the GPR profile is almost the same as the true subsurface structure, because the strongest reflection is measured when the antennas are located just above the reflecting point. In many cases in geological survey, this can be applied.

Fig.4.2 shows one example of actual GPR profiles. In this example, we have three steel pipes buried at 75cm below the ground surface. The corresponding three hyperbolic curves can be observed. A boundary of filled soil and the mixture of concrete and soil is located at 2.75m. This layer is almost flat, therefore, it is directly imaged. We also observe some disturbance of reflected signal at 3.75-5m, and we expect there are some buried objects.



(a)Plane Reflector



(b)Point Reflector

Fig.4.1 Radar Profile and Subsurface Structure

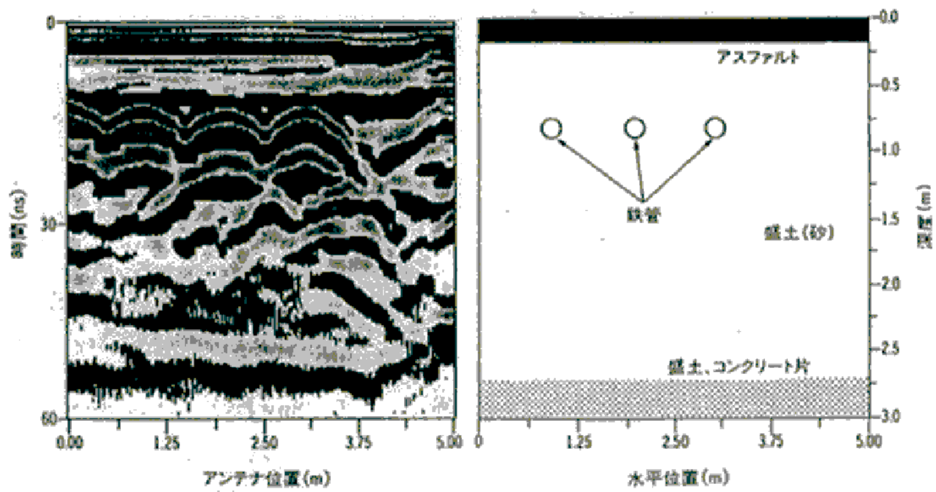
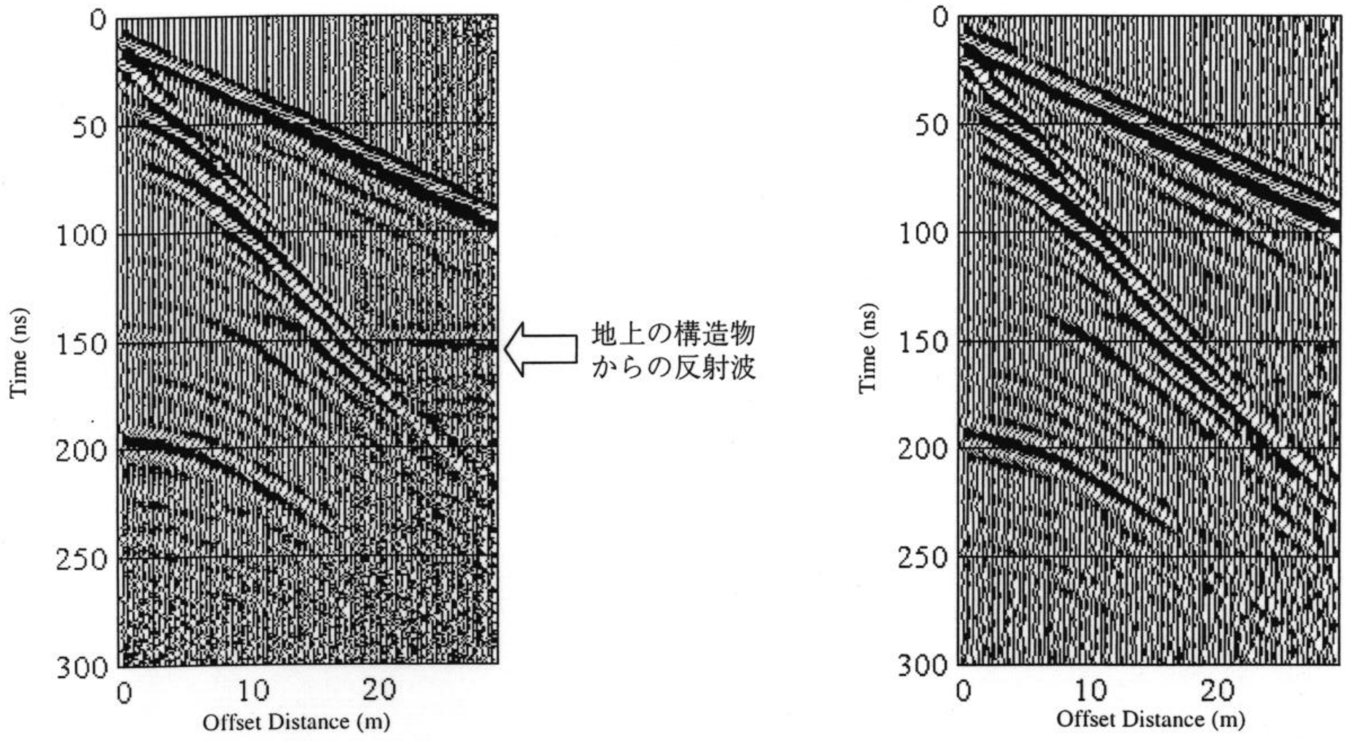


Fig.4.2 GPR Profile from metallic pipes

4.2 Signal Processing

Pre-Processing

Fig.4.3 shows the GPR Profile of the wide angle(CMP) measurement. When the antenna separation gets larger, the arriving time of the signal delays. The directly coupled signal, which propagates from the transmitting antenna to the receiving antenna through air, which is often referred as “air wave” has a straight arriving time delay, but the reflected signal form subsurface objects are on a curved line. The reflection from an object on the ground surface, which is standing on the line of antenna movement does not change in time. We can use this arriving time information for discriminating each object, which causes the reflection.



(a)Raw Signal （ｂ）Signal after rejection of the high frequency noise and reflection from an object above a ground surface.

Fig.4.3 CMP measured signal

This GPR profile is acquired by unshielded antennas. The noise rejection can be processed by a band-pass filter for time domain signal, and two dimensional filter such as f-k filter are effective. Fig.4.3 shows an example of a signal after rejection of the high frequency noise and reflection from an object above a ground surface by the f-k filtering.

In the profile measurement, we sometimes encounter a strong reflection form metallic objects on the ground surface such as steel fence. Identification of such a reflection signal is difficult in the profile measurement. The EM wave velocity in subsurface material and I air is very different, therefore, it is easy to discriminate them by the wide-angle measurement.

Estimation of the Dielectric Constant

When we have a subsurface reflection object whose depth is known, the EM velocity can be determined by the measured travel time. Even when we do not know the exact buried depth, a strong point reflector such as a metal pipe show clear hyperbolic reflection curve, and we can estimate the depth of the object and the velocity simultaneously. When the buried object is located at depth of d and the horizontal distance of x_0, and assume the

EM wave velocity as *v*, the travel time of the reflected signal from this object can be give by:

$$\tau = \sqrt{(x-x_0)^2 + d^2} \Big/ 2v \qquad (4.1)$$

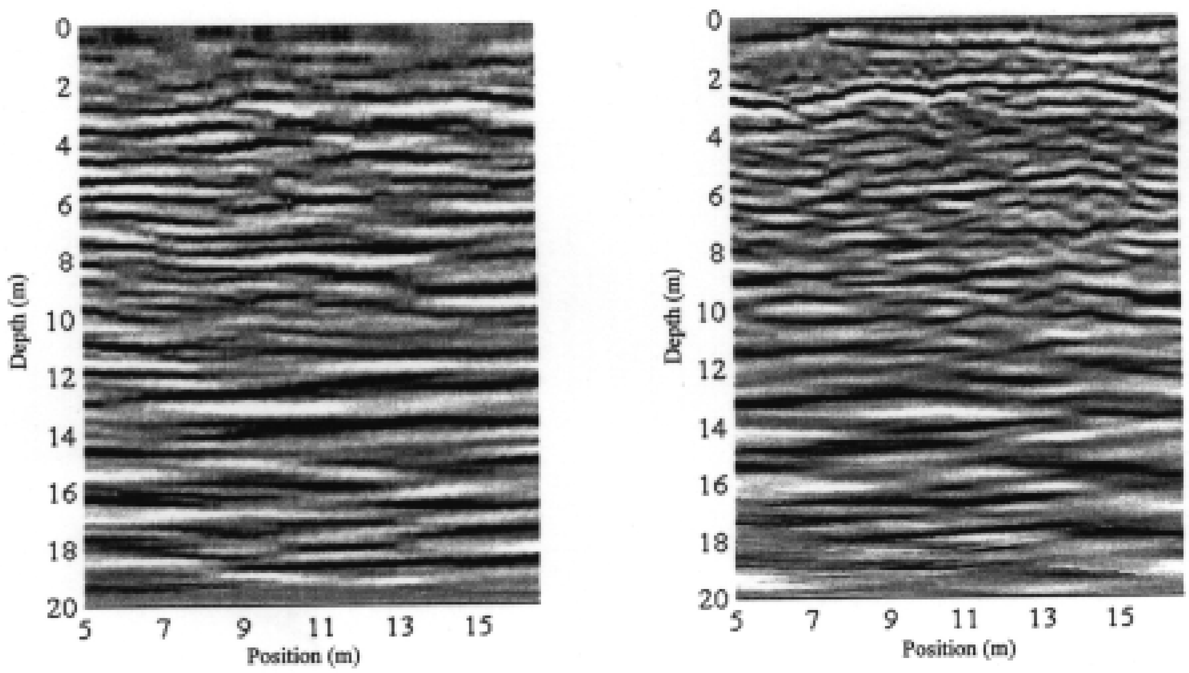
Eq. (4.1) contains three unknown parameters; *d*, *v* and x_0. When we have a clear hyperbolic curve as shown in Fig.4.2, we can graphically fit the theoretical curve and estimate these parameters.
In the wide-angle measurement, when the antenna positions are fixed, theoretical travel time can be calculated as shown in Fig.3.7 and Fig. 4.3 and the EM velocity can be estimated. By the wide-angle measurement, we can use reflecting objects such as a horizontal boundary, and inclined boundary, even multiple boundaries. Many signal processing techniques develop for seismic signal processing can be applied for GPR analysis.

CMP Processing

This technique has been widely accepted in seismic signal processing. In GPR, EM wave is sometimes suffered from a strong attenuation and dispersion. In this case, the signals measured at different offsets lose the coherency and the CMP technique cannot be applied. However, we have found in many cases in dry soil and crystalline rock, CMP for GPR is an effective processing.
The wide-angle measurement and the profile measurement for the same site is compared in Fig. 4.4. Both GPR profiles have many similarities, although SNR and continuities of the reflections are improved in the wide-angle measurement. However, the wide-angle measurement requires much more data acquisition compared to the profile-measurement. One of the most significant advantages of the GPR measurement is the fast data acquisition. CMP cannot use this advantage, so it should not always used. Also, we can find that the radar resolution in shallow region is better in the profile-measurement. It will be cause by the low spatial coherency of the measured signals in the wide-angle measurement.

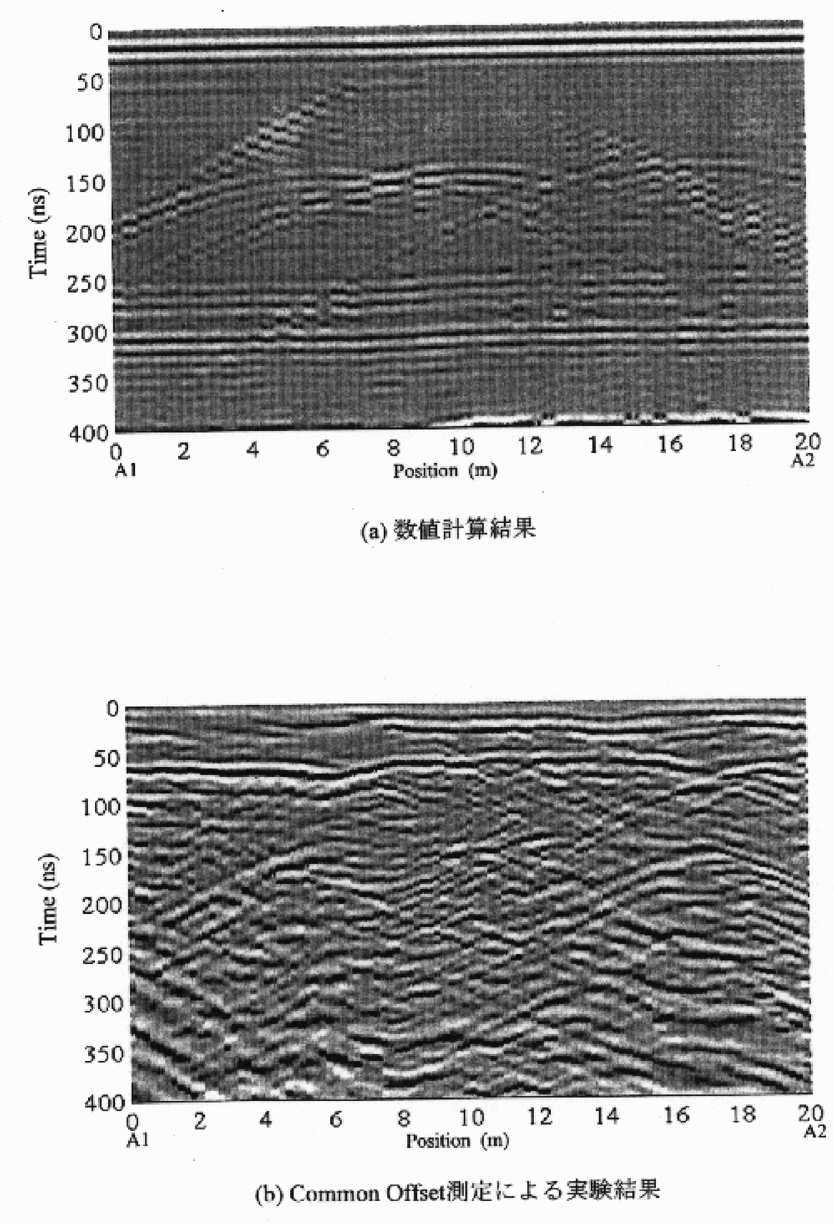
Interpretation

GPR signal interpretation has many similarities to the seismic signal interpretation, and many techniques developed for seismic signal processing are used in GPR. However, the most important differences of the seismic



(a) Wide-Angle Measurement (b) Profile Measurement

図 4.4 GPR Profiles obtained by Wide-Angle and Profile Measurement



(a) 数値計算結果

(b) Common Offset測定による実験結果

図

Fig. 4.5 FDTD simulation

survey and the GPR survey is the time for data acquisition and interpretation. In many applications of GPR, the data acquisition is quick and the signal is interpreted on site in real time. On the contrary, seismic survey needs much longer time and interpretation cannot be carried out in real time. GPR uses this advantage and can be used for on–site detection of buried objects.

Seismic survey and GPR survey has the similarity in the point that both techniques use wave phenomena. When the wavelength used for measurement is much shorter than the size of the measured objects, the interpretation is easy, because diffraction effect is small. This condition is normally satisfied in optics and seismic survey. When this condition is satisfied, we can use a ray theory for calculating the travel time of the reflected wave. In the ray theory, we can use Snell's law for determining the direction of the wave reflected and refracted at the boundary of two materials. The theoretical travel time and the measured one are compared and we can obtain the estimated model of the subsurface structure.

In GPR survey, however, in order to reduce the attenuation of EM wave, we have to use low frequency and the wavelength is the equivalent or larger than the objects. Of course the Snell's law stands in this case, too, but the energy is not concentrated along the ray path and spread. Therefore, the idea of an arrival time is sometimes not very clear, because the dominant part of the energy does not propagate along the ray-path. In such a case, a full-wave simulation of wave propagation is required. Finite Difference Time Domain (FDTD) is the most popular technique for this simulation. The measured GPR profile and the simulated profile by FDTD are compared in Fig. 4.5.

3-D GPR Display

A single GPR survey gives us a vertical profile along the survey line. This is a 2-D model of the subsurface structure. If we set many survey lines, we can obtain the 3-D model. In most GPR profiles contains many noise. If we observe the 3-D model by GPR profiles, we can observe the continuity of reflection waves and we can discriminate real reflections from random noise.

3-D model of the GPR profile scan be constructed by actual model by plastic plates, and by software. I this seminar we show the following examples:

(1)GPR profiles created by Power Point
(2)Animation by Video Clip

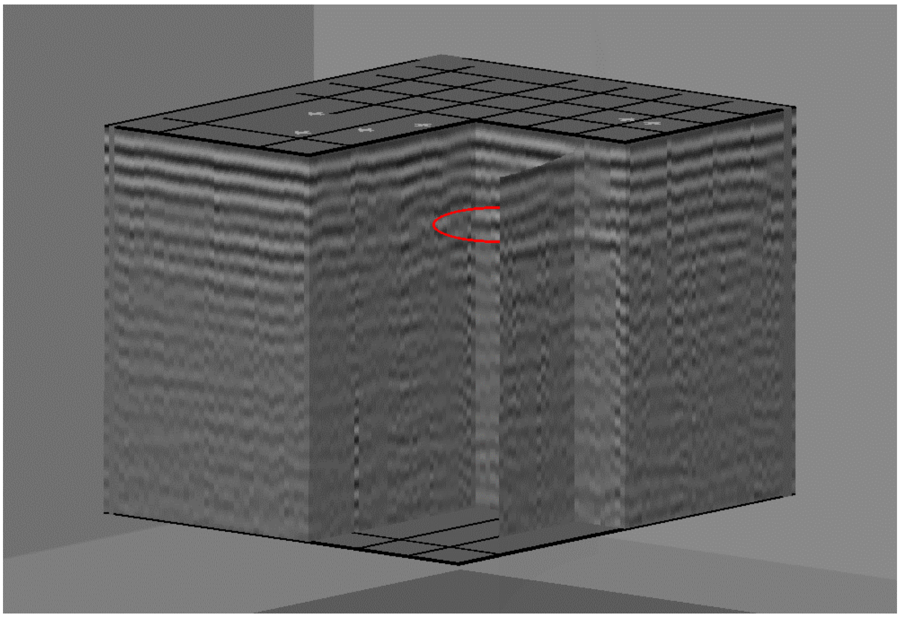


Fig. 4.6 3-D Display of GPR Profiles

5 Undesired Radiation

It is known that EM wave has some interaction with human body. It is also known that EM apparatus such as mobile telephone causes some problems against medical electrical equipment such as hear pace maker.

GPR systems operate in wide frequency range spreading 100MHz to 1GHz. The frequencies in this bandwidth are used in many communication and broadcasting systems. The undesired radiation from GPR system can violate these equipments, so we have to pay attention to the undesired EM wave radiation. The law regulates the use of frequencies, and it can sometimes also applied to other geophysical exploration apparatus.

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