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Highly efficient CMP surveying with ground-penetrating radar utilising real-time kinematic GPS

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ABSTRACT

The main purpose of this paper is to describe a highly efficient common mid-point (CMP) data acquisition method for ground-penetrating radar (GPR) surveying, which is intended to widen the application of GPR. The most important innovation to increase the efficiency of CMP data acquisition is continuous monitoring of the GPR antenna positions, using a real-time kinematic Global Positioning System (RTK-GPS). Survey time efficiency is improved because the automatic antenna locating system that we propose frees us from the most time-consuming process – deployment of the antenna at specified positions. Numerical experiments predicted that the data density and the CMP fold would be increased by the increased efficiency of data acquisition, which results in improved signal-to-noise ratios in the resulting data.

A field experiment confirmed this hypothesis. The proposed method makes GPR surveys using CMP method more practical and popular. Furthermore, the method has the potential to supply detailed groundwater information. This is because we can convert the spatially dense dielectric constant distribution, obtained by using the CMP method we describe, into a dense physical value distribution that is closely related to such groundwater properties as water saturation.

INTRODUCTION

There are many problems due to human activities in the shallow subsurface to which solutions are urgently sought, such as: remediation of groundwater contamination, detection of voids under roads, and elimination of landmines. However, it is often the case with such problems that we cannot examine the survey targets directly, because they lie beneath built structures, or must be left undisturbed. For such applications, geophysical prospecting techniques are required that have the best accuracy and resolution. GPR is one of the most convenient and suitable tools for surveying such shallow subsurface environments.

A GPR data set is similar to a seismic reflection data set because it results from phenomena of wave propagation. This means that we can utilise the excellent heritage of seismic data processing methods for GPR data processing. The CMP method, which forms the backbone of seismic reflection data processing, can be imported successfully to GPR data processing, and has shown excellent results (Fisher et al., 1992).

CMP data acquisition and processing technologies were introduced to seismic reflection surveying in the 1960s (Mayne, 1962), and rapidly became one of the most common seismic reflection survey techniques. The CMP method was imported to GPR surveys in 1971, for ice-thickness measurement, by Gudmandsen. In that experiment, CMP data were acquired only at a few points, for velocity analyses. With further development of acquisition technology, the CMP data acquisition method came to be routine, associated with the high-speed sampling capability of advanced GPR data acquisition systems (Davis and Annan, 1989). The CMP data processing method gave good results for surface-scattering noise recognition and reduction (Sun and Young, 1995), and for multiple reflection suppression (Pipan et al., 1999). Subsequently, Greaves et al. (1996) showed that NMO velocity distributions obtained from velocity analyses can be converted into a map of water saturation, in a new application of GPR surveys.

From now on, we will refer to this method as the "GPR-CMP" method in this paper. Recently, the GPR-CMP method has been tested using antenna arrays. Because an antenna-array system can obtain several antenna-pair data sets simultaneously, acquisition is several times faster than with conventional single-pair antenna systems; the system is therefore quite cost-effective. Such a system could be applied to several applications, such as high-speed and high-resolution detection of cavities under the paved roads, and high-accuracy surveys for land mines (Sato et al., 2004).

The GPR-CMP method can significantly improve signal-to-noise ratio, but a spatially continuous full-coverage CMP survey, unlike conventional GPR-CMP data acquisition at one or a few stations to determine wave velocities, is rarely performed in routine commercial surveys. One reason is that a common-offset gather, which is one conventional method used in commercial GPR surveys and which requires constant transmitter-receiver antenna separation, does have sufficient signal-to-noise ratio for the current targets of commercial GPR surveys. Another reason is that the GPR-CMP method requires much time and effort, and is often more expensive than direct excavation of the survey targets. However, some kinds of survey target may be altered by excavation, and the GPR-CMP method has the advantage of offering non-invasive inspection. Reduction of the costs of the GPR-CMP method could mean a break-through in its availability and application; therefore, in this paper we propose an efficient data acquisition process for the GPR-CMP method.

Nakashima et al. (2001) insisted that it is better to transform common-source gathers to CMP gathers for imaging a section, and to use specifically recorded CMP gathers for velocity analysis, because although the latter method gives higher quality by acquiring a higher number of stacking folds, it is difficult to apply over a wide area. Therefore, if the common-source or common-receiver gather method could be modified to acquire enough stacking folds, it would be a reasonable method with which to provide all types of data. The efficiency of GPR fieldwork might

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be improved with improved geodetic technology. If GPR antenna locations can be measured continuously, data acquisition can be performed with the GPR antennas moving continuously. We can then avoid the troublesome work of positioning the antennas exactly at their required locations (Onishi et al., 2004).

Taking into account the cost, operability, and required positioning accuracy, two geodetic technologies are suitable for our purposes. One is auto-tracking of total stations (Lehemann and Green, 1999), and the other is the Global Positioning System (GPS). Both techniques can measure positions of the GPR antenna accurately as it is towed. The total station system has superior horizontal accuracy (3 mm) but requires line-of-sight between stations, so it can be difficult to use in urban regions. On the other hand, GPS, utilising satellites, requires clear view of the sky. GPS is comparatively more advantageous for surveys carried out in urban regions because a clear view of the sky is normally available. Real-time kinematic GPS can measure absolute positions to within a horizontal accuracy of 1 cm (Onishi et al, 2004), which we judge is sufficient for GPR antenna-location purposes.

A field experiment reveals the effectiveness of the GPR-CMP method with RTK-GPS, by showing how the CMP fold is improved in this way.

No geophysical surveys are better than the GPR method for imaging the shallow subsurface down to several metres in depth, with high resolution. High quality data are usually obtained with a conventional common-offset GPR survey in mid-latitude humid areas such as Japan, but the penetrating depth of GPR into humid soil is generally limited to about 5 m. Human activities in recent times, however, have increasingly affected the depth range from 5 m to 10 m, and many environmental or civil engineering issues have arisen there. Because the GPR-CMP method can image deeper subsurface structures, using CMP stacking techniques, it is one of the most promising methods for imaging in these depth ranges, and we anticipate that the demand for high-density GPR surveys using accurate geodetic techniques will increase in the near future.

METHODS

An efficient GPR-CMP data acquisition method

In normal GPR surveying, CMP gathers are obtained only for determining vertical velocity structure at particular points. These CMP gathers are generally recorded by fixing the mid-point between transmitter and receiver antennas, and moving both antennas outward (Figure 1a). This provides one full-fold CMP gather at one CMP location, and is suitable for precise velocity analysis; however, if the number of CMP points is increased, data acquisition loads are increased and the survey procedure becomes impractical. Therefore, an alternative, simpler acquisition method, fixing one of the antennas as shown in Figure 1b, may be used to acquire more CMP data (Fisher et al., 1992; we refer to this as "the reference method" in this paper). After recording, the data volume can be sorted into any order, to produce common-receiver gathers, common-midpoint gathers, or common-transmitter (source) gathers, as is done with seismic reflection data.

Our proposed data acquisition procedure shares certain similarities with that of the reference method, in that both methods have a "fixed" antenna and a "moving" antenna. The most important difference between the two is the philosophy of moving antenna deployment. The reference method sets the moving antenna at an antenna station and acquires a trace of data at each station.

In contrast, we suggest the unique idea of measuring the antenna positions continuously with geodetic techniques. A normal GPS supplies positioning data every second, so we could interpolate to obtain intermediate antenna positions, and so measure the moving antenna locations everywhere on the antenna path. For more-accurate interpolation, we could also equip the GPS antenna with an accelerometer, in case antenna speed changes more rapidly. Note that a single data trace of the GPR is quite short in time, and one can record a large amount of continuous data with recent GPR systems.

We now discuss the way to determine the "virtual" moving-antenna locations (Figure2). The first point to be discussed is the interval between spatial sampling points in the field. This should be minimised taking into account conditions such as the capacity of the GPR recording system, GPS accuracy, and maximum tolerance for position interpolation. Because the moving antenna usually moves relatively slowly, acquisition usually over-samples the subsurface. Such spatial over-sampling enables us to define the locations of virtual antennas flexibly, by summing spatially spread data at the post-survey data-processing stage. Figure 2 is a schematic diagram of virtual antenna locations when the actual sampling point interval is 3 cm. Three virtual antenna intervals of 15 cm, 30 cm, and 50 cm are illustrated.

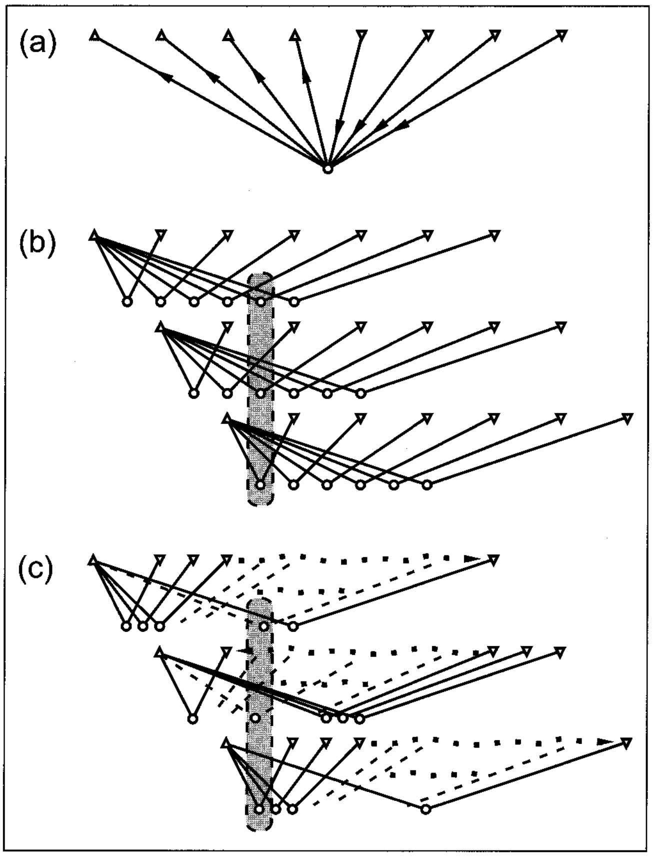

Fig. 1. Schematic diagram of the antenna and CMP positions used by three different GPR-CMP methods. (a) General CMP gathers of GPR for determining vertical velocity structure. A full-fold CMP gather is obtained with fixing the midpoint between transmitter and receiver antennas, and moving each antenna away from the midpoint. (b) Data acquisition strategy for most current GPR-CMP surveys (Fisher et al., 1992). Only one antenna is moved while the location of the other antenna is kept fixed. The fixed antenna is moved after each source gather is completed. (c) Our proposed efficient GPR-CMP data acquisition procedure. The method continuously measures the antenna positions automatically using geodetic techniques. One antenna is kept fixed while the second antenna is moved continuously, as in (b), but the second antenna is not placed at specific stations.

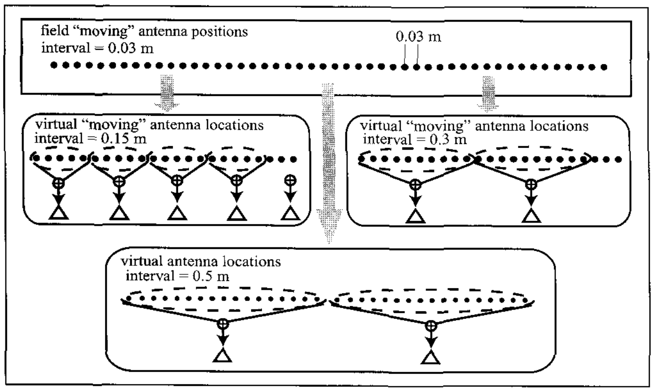

Fig. 2. Schematic diagram of the procedure to determine the virtual locations of the moving antenna. Black solid circles show the locations of actual field sampling points. Open triangles indicate the locations of the virtual antenna, showing how different antenna spacings can be achieved by summing groups of actual traces. If we acquire spatially dense data in the field, the virtual antenna locations can be determined flexibly during post-survey data processing.

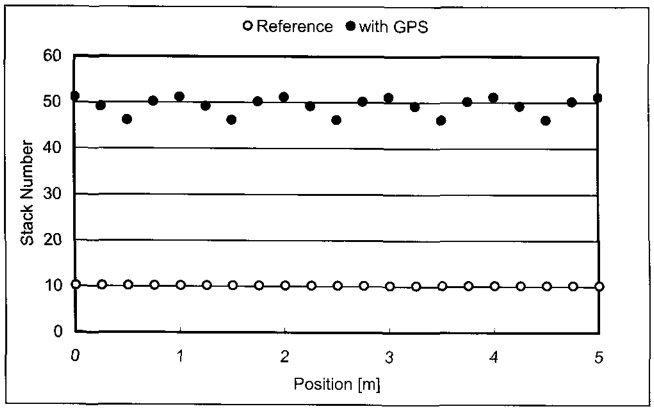

Fig. 3. Comparing the typical number of CMP stacking fold of the reference method (Fisher et al., 1992), and our proposed method. The CMP stacking fold is approximately inversely proportional to the CMP interval. In this case, the CMP interval of our new method is 1/5 of that of the reference method, and the stacking fold is 5 times that of the reference method.

Such ideas are similar to array-forming processing in a marine seismic survey in which all raw data from each hydrophone is acquired. As surface-wave and swell noise are reduced by using such arrays in a seismic survey, so we expect to reduce the noise from coherent noise wave groups having apparent velocities far different from reflection events, such as direct waves, air waves, and ringing, in GPR surveying.

Our proposed procedure minimises the effort required in locating the moving antenna, and also leads to the acquisition of greater volumes of data than the reference method. The increase also leads to dense spatial coverage and high CMP fold, and we will also show that our method leads to much higher signal-to-noise ratios than the reference method.

Let us briefly consider the relationship between the data acquisition load and signal-to-nose ratio. We begin by considering the reference method. This method is effectively identical to seismic reflection data acquisition; it can easily be understood by analogy with seismic surveys. The number of CMP stacking folds is simply proportional to the number of receiver (moving-antenna) locations. Therefore, if the number of antenna locations is increased by a factor N, the signal-to-noise ratio is improved by a factor of $\sqrt{N}$. However, our method could theoretically increase the number of moving-antenna locations almost to infinity, limited only by the recording system capabilities. Suppose that our method results in α times as many moving-antenna positions as the reference method, the stacking fold may then become αN, and the improvement in signal-to-noise ratio improvement is $\sqrt{(\alpha N)}$. Large amounts of data, apparently corresponding to $\alpha > 1000$, can be acquired with our proposed method. In practice, α lies between 5 and 20. A practical limit to the number of moving-antenna locations in our method is that the data acquired from spatially close reflection points are identical and do not contribute to coherent noise suppression by CMP stacking.

Distributions of stacking fold and evaluation of data density

When GPR-CMP data are acquired at constant sampling time intervals, the spatial data density tends to increase with depth. In

CMP survey method	Reference	with GPS
Receiver interval	1 m	1 m
Transmitter interval	0.5 m	0.1 m
Transmitter-receiver distance range	1 m – 20.5 m	1 m – 20.5 m

Table 1. Parameters for calculation of typical numbers of CMP stacking folds.

Survey method	Reference	with GPS 1	with GPS 2
Receiver interval	1 m	1 m	2 m
Transmitter interval	0.5 m	0.0625 m	0.03125 m
Vertical stack number	8	1	1
Sampling interval	0.5 ns	0.5 ns	0.5 ns
Wave velocity	0.07 m/ns	0.07 m/ns	0.07 m/ns
Transmitter-receiver distance range	1 m – 12 m	1 m – 12 m	1 m – 12 m

Table 2. Parameters for calculation of spatial data density distribution.

CMP30 (15.0m)		CMP40 (20.0m)		CMP50 (25.0m)	
Two-way time [ns]	Velocity [m/ns]	Two-way time [ns]	Velocity [m/ns]	Two-way time [ns]	Velocity [m/ns]
112	0.079	113	0.080	143	0.081
153	0.077	157	0.074	205	0.082
222	0.073	235	0.072	224	0.082
-	-	294	0.070	277	0.072

Table 3. The results of velocity analyses shown in figure 12.

the shallower portions of a gather corrected for normal moveout (NMO), it is readily observed that insufficient data density results in NMO stretch. A goal of careful survey design should be to limit NMO stretch, because it distorts the resulting subsurface image. Generally, dense horizontal data sampling limits the effects of NMO stretch to the shallow zone on the image. We can estimate the zone which is unaffected by NMO stretch from the data density map, and take precautions to reach an adequate data density below the uppermost part of the target zone.

On the other hand, we can improve survey efficiency by reducing the number of observation points, if sufficient data density is assured. In the reference GPR-CMP experiment, the observation-acquisition effort is almost halved by setting the fixed-antenna intervals to be double the moving-antenna intervals. Here, we compare the fold achieved by the reference GPR-CMP method with that by our GPR-CMP method. The experimental parameters are indicated in Table 1, and a horizontal bin size of 0.25 m was used. Figure 3 shows the synthetic stacking fold numbers calculated. Generally, fold is closely related to the horizontal data acquisition spacing. If the CMP bin is sufficiently large, the CMP stacking fold is almost inversely proportional to the CMP interval. In this case, as shown in Table 1, the CMP interval of our proposed method is 1/5 that of the reference method, and the stacking fold is almost 5 times larger, as expected.

Next, we study data density distributions in 3D space, to evaluate the effect of NMO stretching. Horizontal bin size was maintained at 0.25 m; vertical size is defined to be 0.0625 m based on sampling with a 100 MHz waveform. We assume homogeneous media with an electromagnetic wave velocity of 0.07 m/ns. As shown in Table 2, we compared three conditions. The first condition corresponds to the reference method with the same parameter set as above and with the number of vertical stacks set to be eight. The second and third conditions simulate our newly proposed method with different fixed (receiver) antenna intervals. In one case, the fixed-antenna interval is the same as that in the previous numerical experiment. The moving-antenna interval in this case is 0.0625 m, giving the same data volume as the reference method. In the second case, the fixed-antenna interval is twice as long and the moving-antenna interval is halved. This is significant is it suggests that we can halve the survey cost using the second case, if we judge the stacking fold to be sufficient.

Figure 4 shows the distribution of data density. Comparing the results we see that the zone of high data density is clearly distributed around the moving-antenna positions in the reference method image; the data density variation of our proposed method is, however, spatially smooth. This phenomenon can be explained in observing that the increase in the number of antenna locations results in a spatially uniform distribution of reflection points. The proposed method does have sufficient data density at the shallower portion. If we interested only in deeper targets, on the other hand, we can reduce the number of redundant moving-antenna locations, and the survey can be performed more efficiently.

There is a further very important factor that we have not yet discussed in the paper: the survey time. This reflects directly on the survey cost. Figure 5 compares the survey efficiency of our proposed method with that of the reference method. Data acquisition parameters for both cases are again as those shown in Table 2.

Figure 5(a) shows the relationship between survey time and the number of GPR antenna locations, from which it can be seen that our proposed method is five times faster than the reference method. As indicated in Figure 5(b) by the number of acquired traces, the ratio between the two methods is directly related to that of acquired data density. Note that the parameters shown in Table 2 were determined to maintain constant data volume, without considering survey time. These results also show that it will take time about 40 times as long to acquire dense CMP gathers at the same interval as our proposed method, using the reference method.

Recently, data-sampling capabilities of GPR data acquisition systems have been getting faster almost day-by-day. Today, we can acquire a GPR cross-section having sufficiently dense trace intervals using a vehicle-towed system. On the other hand, data acquisition using a human-towed antenna results in movement of the GPR antenna that is much slower than maximum data acquisition speed allows so that the capabilities of the data acquisition system

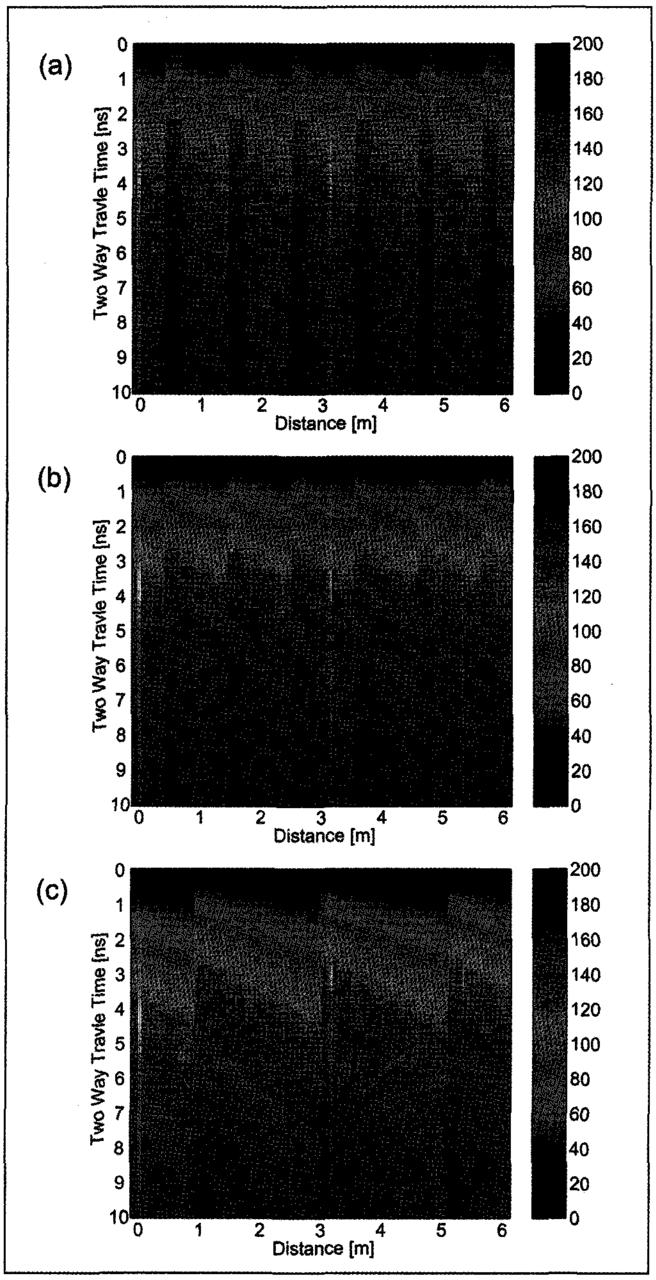

Fig. 4. Data density of (a) a conventional common offset GPR survey, (b) the reference method (Fisher et al., 1992), (c) a dense receiver-interval instance of our CMP-GPR method using GPS, and (d) a sparse receiver-interval instance of our method. The colour legend is the number of folds in a rectangular bin (0.2 m × 0. 0625 m). The reference method acquires data with one antenna fixed, resulting in a variation in stacking fold density. Our method shows a comparatively gradual change in stacking fold density.

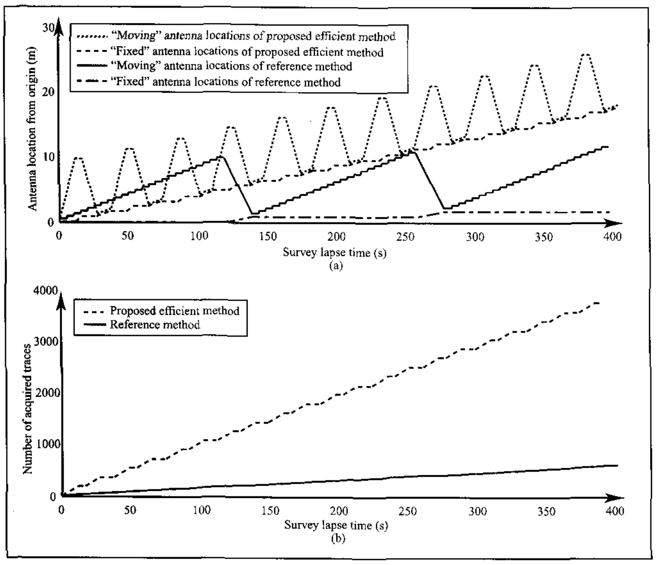

Fig. 5. Comparison of survey efficiency of our proposed method with the reference method (Fisher et al., 1992).
(a) Comparison of the rate of occupation of GPR antenna locations.
(b) Comparison of the rate of acquisition of GPR data traces.
Data acquisition efficiency of our proposed method is more than five times than that of the reference method.

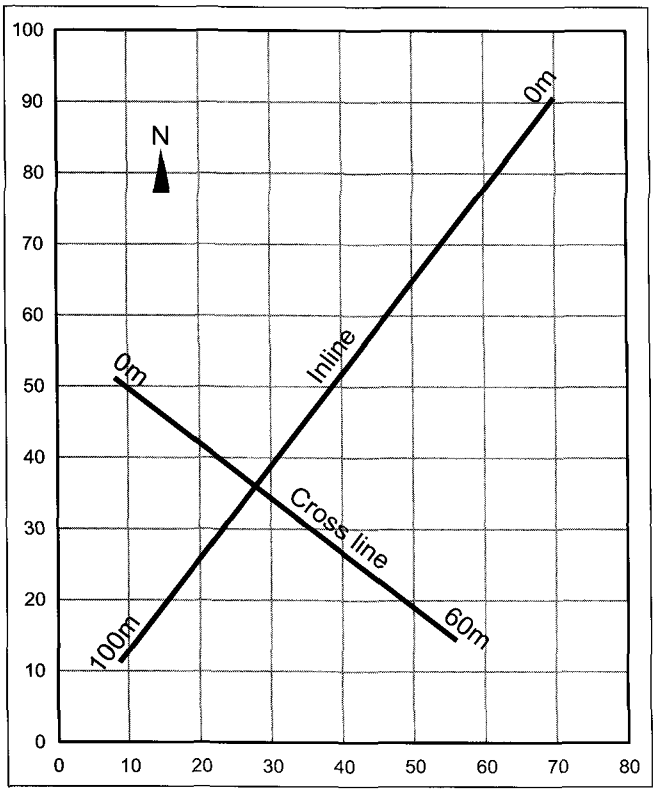

Fig. 6. Two survey lines at the Tsukuba Technical Research and Development Center of OYO Corporation, Japan. The positions of survey lines were measured by RTK-GPS.

Fig. 7. Photograph of the experimental field.

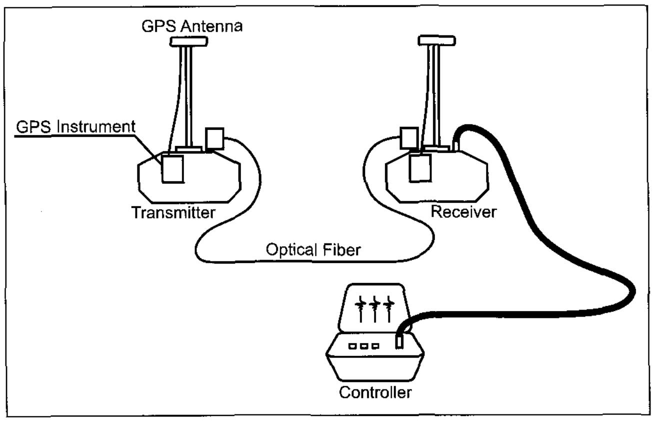

Fig. 8. A schematic view of the GPR system with RTK-GPS. During data acquisition our GPR-CMP survey method, the movement of each GPR antenna is quite complicated. However, the GPS system (GPS antenna and recording unit) deployed on each GPR antenna measures the complete trajectory of the antenna.

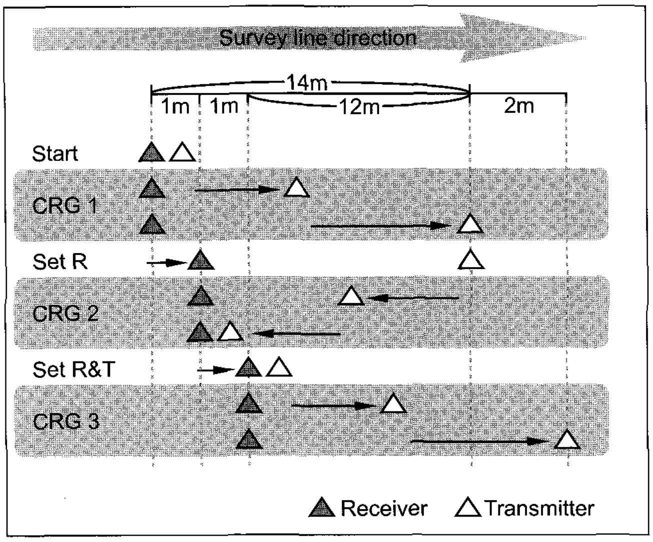

Fig. 9. A schematic view of the procedure in our efficient CMP method. The receiver is placed at a station, followed by a common-receiver gather (CRG). Transmitter and receiver antennas are moved in turn. Note that "Set R & T" begins a new cycle, one station advanced from "Start". During these operations, the GPR instrument records continuously.

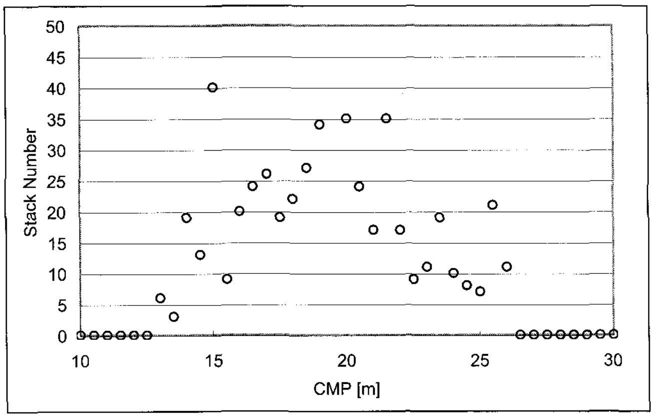

Fig. 10. The distribution of CMP stack number in the experimental data. A complete data set was only acquired between CMPs 12.8 and 25.8.

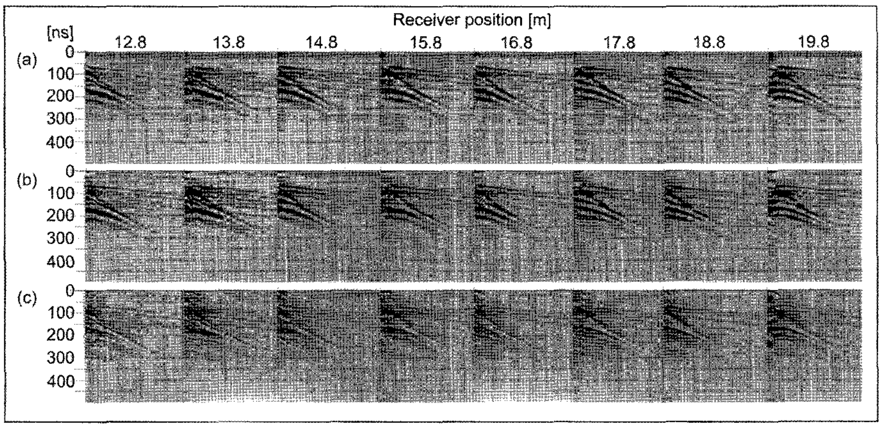

Fig. 11. Common-receiver gathers obtained at the receiver positions at 1 m intervals from 12.8 m to 19.8 m, and their processing results. Each figure shows CRGs (a) before processing, (b) after applying a *f-k* filter, and (c) after applying a deconvolution filter, respectively. The *f-k* filter removes coherent noise. The deconvolution filter compresses wave forms to make reflection events sharper and more compact.

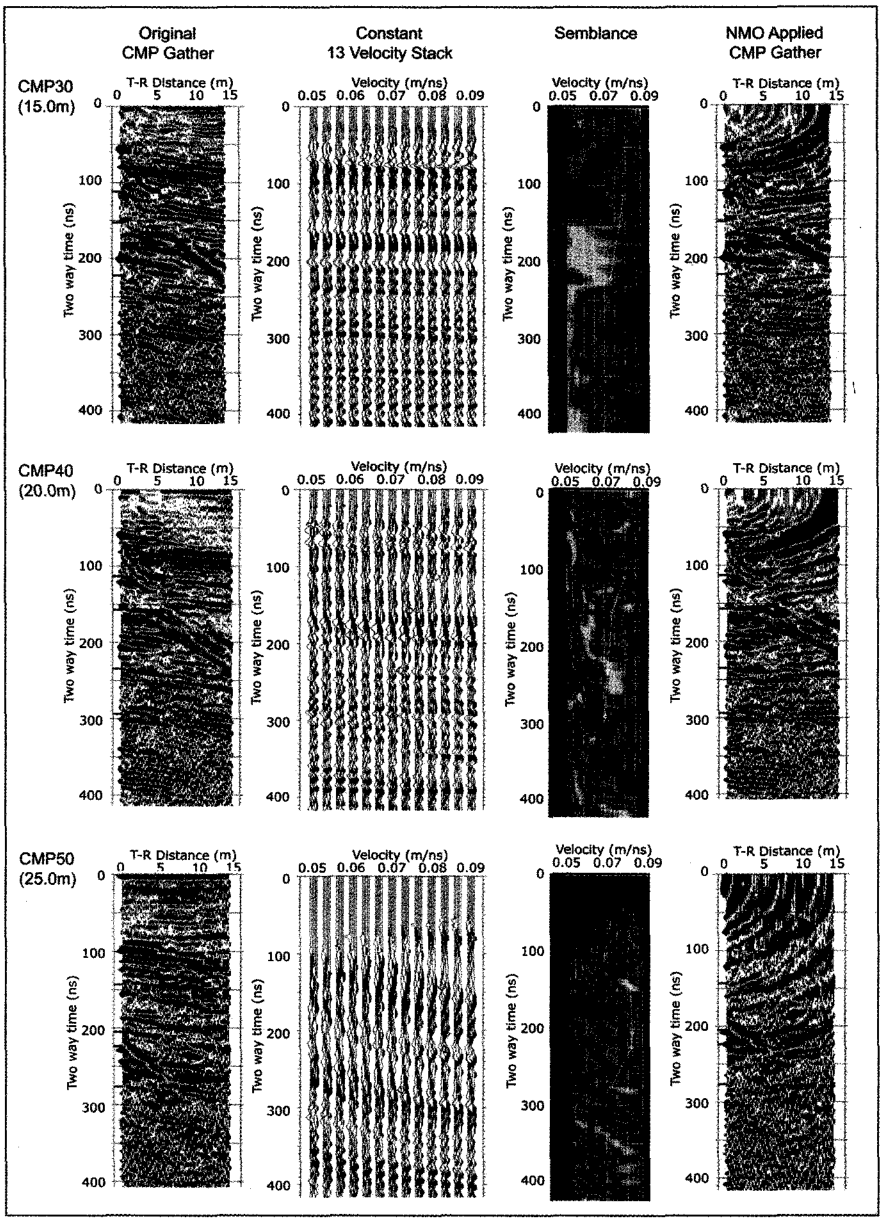

Fig. 12. Examples of CMP gathers and velocity analyses at CMP locations CMP30 (15.0 m), CMP40 (20.0 m) and CMP50 (25.0 m). Original prestack CMP gathers are shown in the leftmost position in each row. Results of constant velocity stacks using 13 constant velocities, followed by their semblance, are illustrated in the middle columns. In the rightmost position in each row, the gathers after applied NMO correction are shown. Diamond symbols in the CV stack and semblance panels show picked velocities.

are not utilized effectively. In such cases, our proposed method can obtain spatially high-density GPR data sets, and the high recording density contributes by increasing the CMP stacking fold. In other words, our method converts surplus performance capability in the GPR instrument into an improvement of the signal-to-noise ratio.

Horizontal positional accuracy of the RTK-GPS is guaranteed to be better than 1 cm. However, planning is needed, because GPS data from a reference station is essentially indispensable to operation of the RTK-GPS. Fortunately, the Japanese government has installed an official reference station in 2003, and the necessary data for RTK-GPS in Japan can be downloaded in real time using a cell-phone. If real-time data is not needed, however, the survey cost can be further minimised by utilising post-survey kinematic GPS corrections. It is good practice to obtain an additional GPS data set at a known geodetic point such as a triangulation control point.

Reduction of random and coherent noise

When we acquire geophysical data, we cannot completely avoid contamination of the data by either random noise or by coherent noise such as ringing or multiple reflections. Random noise can effectively be eliminated by vertical stacking. However, coherent noise is generated by processes associated with the data acquisition, and recorded similarly when using the same data acquisition geometry. Consequently, vertical stacking increases the energy of coherent noise and cannot be removed by that process.

For seismic data acquisition and processing, coherent noise can be reduced by CMP stacking (Yilmaz, 2001), because CMP stacking is a kind of horizontal stacking, utilising the NMO correction to deal with the different propagation paths between different shot and receiver pairs. GPR data contaminated by coherent noise are also improved by CMP stacking (Pipan et al., 1999). The data-acquisition strategy in the GPR-CMP method minimises the number of data pairs recording energy which has travelled along identical ray-paths. This feature leads to coherent noise reduction by CMP stacking.

FIELD EXPERIMENT

We performed a field experiment at the Tsukuba Technical Research and Development Center of OYO Corporation in Japan. Two lines were surveyed; one is 100 metres long in a NE-SW direction, and the other is 60 metres long in a NW-SE direction (Figure 6). Figure 7 is a photograph of the experimental site. In this test, a

SIR2000 GPR controller and 100 MHz GSSI antennas were used. Control signals are communicated through a fibre-optic cable between the transmitter and receiver antennas. As the signal cable between the controller and a receiver antenna is a co-axial cable, it can generate an unacceptable amount of noise if it is dragged around with the GPR antennas. Therefore, the receiver antenna was the fixed antenna, and the transmitter antenna was moved, to minimise the noise generated by the cable. Each GPR antenna was equipped with a RTK-GPS antenna and controller (Figure 8). GPS data were recorded in the GPS data recorder, independently from the GPR controller. To synchronize the GPR and GPS data sets, we recorded absolute time data from the GPS receivers into the GPR recorder for post-survey processing.

Several steps from the actual operating procedure with the antennas are shown in Figure 9. A GPR data set is obtained by repeating the following procedures: (1) the GPR measurement is started with the receiver and transmitter antennas in contact with each other at the first station of the survey line; (2) the transmitter (moving) antenna moves toward the end of the survey line, until the distance between the antennas is 14 m; (3) the receiver antenna moves one metre toward the end of the survey line, and the transmitter antenna is towed back towards the beginning of the line; (4) when the antennas are again in contact, they are moved one metre together toward the end of the survey line. The antenna-movement cycle begins again and the iteration continues until both antennas reach the end of the survey line.

In the test survey we obtained 96 090 and 42 981 data traces along the survey of inline and cross-line directions, respectively, a total of 139 071 traces obtained within only one day (a net survey time of six hours). The numbers of common receiver points are 87 and 47, respectively. There are two types of common receiver gathers, one with maximum offset (antenna interval) of 14 m and the other with a maximum offset of 13 m.

The main hindrance to rapid surveying was the handling of the fibre-optic cable connecting the transmitter and receiver antennas. This cable must be handled very carefully to avoid bending stresses, especially when moving the transmitter antenna, because that changes direction frequently and is moved relatively rapidly. Under such conditions, it is easy to bend the fibre-optic cable excessively. We believe that devising a system to keep the fibre-optic cable tangle-free will considerably increase the efficiency of GPR-CMP surveys.

DATA PROCESSING

Although total trace numbers acquired were over 130 000, because of the failure of the GPS, useful data was limited to the line segment corresponding to the eight fixed antenna locations between 12.8 m to 19.8 m in the inline direction. The number of traces acquired in this segment was 9601. The horizontal bin size was chosen to be 0.5 m for analysis, giving CMP points at 27 locations between 13.0 m to 26.0 m. The distribution of stack number which resulted is shown in Figure 10. Common receiver gathers are shown in figure 11. Figure 11a shows raw data, which includes much noise. Applying a *f-k* filter to the common–receiver data can remove the coherent noise which appears as horizontal linear events in the sections (Figure 11b). A whitening deconvolution filter was also applied to get sharper reflection events (Figure 11c).

Examples of CMP gathers at three CMP locations, CMP30 (15.0 m), CMP40 (20.0 m), and CMP50 (25.0 m), are shown in Figure 12. Prestack CMP gathers are shown on the left in each row. The results of constant-velocity stacks using 13 constant velocities are shown next to the prestack gathers, and the semblances are placed next to them. Finally, the images in the right-most column are CMP gathers after the application of NMO correction. The locations of velocity picks are indicated on some images. The results of velocity analysis are shown in Table 3.

The results of velocity analysis indicate that the velocity of electromagnetic wave propagation is approximately 0.08 m/ns, and decreases with depth in this location. Estimating the distribution of dielectric constants from the results of velocity analyses at many points gives a physical property map, which we expect to be a valuable product of GPR surveying in the future. The distribution of dielectric constant is relevant to surveys for NAPL contaminants, and hydraulic conductivity (Goaguen et al., 2001), and that is a significant benefit from full-coverage CMP surveys with GPR.

CONCLUSIONS

A GPR-CMP data set obtained with dense spatial sampling is more useful than conventional common-offset GPR data sets for the following reasons. Firstly, data can be sorted into any of a variety of data domains, such as common-midpoint gather (CMP), common-receiver gather, or common-transmitter gather, and random noise can be reduced in these different domains. Secondly, coherent noise can be suppressed using CMP stacking. Finally, spatial distribution of dielectric constants can be directly calculated from the results of velocity analyses.

Despite such advantages, the GPR-CMP method has not been widely utilized. One of the main reasons is the cost of such a survey – the GPR-CMP method has required many times more effort as conventional methods. Therefore, in this study, we have proposed an efficient GPR-CMP data acquisition system in which moving-antenna locations are continuously monitored by RTK-GPS. This method substantially reduces the survey cost because the moving antenna need not be deployed at exact positions. Moreover, the method improves the quality of data acquired, because of an improvement in the CMP stacking fold, which is achieved because virtual moving-antenna locations can be determined by post-survey array forming.

We carried out a basic field experiment with our proposed method with the following results. As expected, data acquisition efficiency of this method was high, with 160 m of GPR-CMP profile, covered by 139 071 data traces, obtained in six hours net of survey time. In the data processing sequence, possibilities for improvement in data quality were indicated, because the data set allowed a variety of filter operations in various data domains.

In conclusions, we would like to re-emphasise that our GPR-CMP method will also be important for studying subsurface rock, soil, and water properties, because the method effectively allows the imaging of subsurface dielectric constant distributions. We hope that our new method results in a wider scope for GPR applications in the future.

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キネマティックGPSの同期による地中レーダCMP探査の高効率化

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要　旨： 地中レーダの適用用途拡大を目指し、効率的なCMP探査手法を提案する。地中レーダのCMP探査はコヒーレントノイズ改善効果が確認されている。また、速度解析から水分率の空間分布図の提供が可能となり、効用は大きい。しかし、1対のアンテナで行うCMP観測の費用対効果は低く、商業利用で行われることは希であった。そこで、本研究では、水平精度1cmのリアルタイムキネマティックGPSを用いて地中レーダアンテナの観測位置を高精度で自動計測し、CMP観測に要する作業量の軽減と重合数の増大を図った。まず、連続走査状態でも地中レーダアンテナの観測位置精度が十分に確保され、通常の固定オフセット探査よりも精度を要し作業が煩雑なCMP観測時のアンテナ位置固定作業が不要となる。さらに、機器の高性能化から、通常、超過サンプリングとなる取得記録の全てをCMP記録として観測可能となるため、既存の地中レーダCMP観測法よりもCMP重合数の増大が見込まれる。本研究では数値計算を行い、提案手法が従来法に比べCMPのデータ密度や重合数が増加することが示された。また、提案手法をフィールド調査に適用し探査の実現性と高速性が検証された。その結果，1時間当たりの探査作業で，ビンサイズ50cm当たり約500トレースの記録が，約20m分観測可能であった．取得された記録トレースは垂直重合とCMP重合に自由に分配可能で，最適な観測仕様の設定が処理段階で行える．地中レーダの商業観測においてCMP法の選択が可能となり、地中レーダ観測適用用途の拡大につながるものと考える。

실시간 GPS를 이용한 고효율 GPR CMP 탐사

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요　약： 이 논문의 주 목적은 효율이 높은 공통중간점(CMP) 자료 획득 방법에 대해 서술함으로써, GPR 탐사의 적용성을 넓히기 위함이다. CMP 자료 획득의 효율을 높이기 위한 가장 중요한 기술적 혁신은 실시간 이동 GPS(RTK-GPS)를 이용한 GPR 안테나의 위치 연속 모니터링이다.

이 연구에서 제안한 자동 안테나 이동 시스템은 GPR 탐사에서 시간을 가장 많이 요구하는 특정 지점에 안테나를 위치시키는 과정이 필요없기 때문에 탐사 시간 효율이 개선된다. 수치적 실험으로부터 자료획득 효율이 향상됨에 따라 자료의 밀도 및 CMP 중합수가 늘어나는 것을 예측할 수 있었으며, 이는 결과적인 자료의 신호대 잡음비 향상을 초래한다.

현장 적용은 이러한 가설을 입증하였으며, 이 연구에서 제안된 방법은 CMP 방식의 GPR 탐사를 좀 더 실질적이고 널리 사용될 수 있게 한다. 게다가 이 방법은 정밀한 지하수 정보를 제공할 수도 있는데, 이는 CMP 방식으로 얻은 공간적으로 조밀한 유전상수 분포를 물포화도와 같이 지하수 특성과 관계 깊은 조밀한 물리량 분포로 변환할 수 있기 때문이다.

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