Near Range Radar and Its Application to Near Surface Geophysics and Disaster Mitigation

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ABSTRACT: In this paper, we discuss about the near range radar applied to various environmental applications and disaster mitigation issues. Synthetic aperture radar (SAR) processing or migration is the key technology in near range radar imaging, which can be used in ground penetrating radar (GPR) and ground-based synthetic aperture radar (GB-SAR). We demonstrate some applications which include GPR for humanitarian demining, GPR for archaeological survey, GB-SAR for landslide monitoring and nondestructive inspection of wooden buildings. We also demonstrate a new array GPR system “Yakumo”, which was used for archaeological survey for demonstration of advanced multi-static radar signal processing for better radar imaging.

KEY WORDS: near range radar, GPR, GB-SAR, disaster mitigation, SAR processing, migration, multi-static radar.

0 INTRODUCTION
Since 1980s, ground penetrating radar (GPR) has been widely accepted in near surface geophysics and applied environmental geophysics. It is especially successful in near surface geoeengineering such as buried pipe detection. However, as a radar system, GPR is quite unique, because it is wide frequency range radar, and its targets are very close to the radar system, compared to conventional radar, such as weather radar and air traffic control radar. Most of these conventional type radars used relatively large real aperture antennas for transmitting very narrow beam electromagnetic wave in order to achieve high spatial resolution in azimuth direction. However, the frequency bandwidth is limited, in order to avoid any interference with other systems, because electromagnetic waves will be transmitted to a very wide area. In other words, we have to get legal permission of the transmitting frequency. On the contrary, GPR transmits electromagnetic wave only into subsurface, therefore the transmitting signal is not limited by any regulation, provided that the field strength of the transmitted electromagnetic wave into air is very small, and we can use very wide frequency range. In order to achieve very high range resolution, wide frequency range antennas and radar system were developed for GPR, and currently these technologies are also adopted in the UWB (ultra wide band) communication systems. UWB system can be operated under the condition that the transmitted electromagnetic wave reaches only limited short distance from the radar system.

GPR is typically using the frequency between 100 MHz and 1 GHz. However, due to the limited size of the antenna, radiation pattern of these antennas are relatively wide, and could not have high azimuth resolution, if we uses the raw radar signal. Hence, signal processing including synthetic aperture radar (SAR) or seismic migration processing has been commonly used in GPR signal processing. SAR processing is commonly called “migration” in the field of subsurface sensing or geophysical exploration, however, mathematically SAR processing and migration are similar. If we use SAR processing in near range radar systems, we can achieve very high resolution images, and GPR can be used in many applications. Recently, we have applied this technology in applications in disaster mitigation. In this paper, we will discuss the concept of near range radar imaging and our recent applications.

1 DATA ACQUISITION AND POSITIONING SYSTEM
Synthetic aperture radar (SAR) processing has been widely used in space-borne and airborne microwave remote sensing. When we use SAR processing for GPR data sets, we should notice that the situation is more difficult compared to conventional SAR, because we have to image the near field, and through a very inhomogeneous medium. Most of the SAR image reconstruction use Fourier transformation based imaging approach. The radiation pattern of an array antenna is well understood that the wider array size and denser array spacing gives the narrower beam width, thus we can obtain better azimuth resolution in real aperture radar imaging. In SAR, using radar signal acquired moving along a survey line, and the narrow beam, or high resolution image is equivalently given by a simple image reconstruction algorithm in time domain as

\[ u(x, y) = \int \frac{2R(x'-x, y)}{v_y} \, dy \]

where \( R = \sqrt{(x-x')^2 + y^2} \) is the distance from the antenna position to the imaging point \((x,y)\), \( v \) is the wave velocity in the

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medium. Equation (1) shows that the image is reconstructed by a phase compensation caused by propagation delay $R/v$ to the measured time-domain data $d(x', t)$ acquired at the position $x = x'$.

If the scanning length is unlimited, as the case spaceborne SAR, the Fourier based image reconstruction algorithm gives the azimuth resolution $D/2$, where $D$ is the size of the real aperture used in the SAR system, and this resolution is independent on the distance from the sensor to the objects. This condition will be satisfied, if the data sampling spacing is denser than a half wavelength, which is determined by the Nyquist criterion in Fourier based imaging algorithm.

If we have multi-static antennas, the SAR processing can be expanded into

$$u(x, y) = \sum_i d_i(x', t) \frac{2R(x-x', y)}{v} dx'$$

where $d_i(x', t)$ denotes the time-domain signal of the $i$-th pair of transmitter and receiver antennas. Multi-static radar can acquire radar data from wider incident angles, and it can improve the quality of the reconstructed images.

2 APPLICATIONS OF GPR

We demonstrate in this section some applications of advanced GPR. We think that accurate data acquisition of GPR data sets and effective signal processing, principally by SAR processing is the key issue in these applications.

2.1 Applications to Land Mine Detection in Humanitarian Demining

Many researches have attempted to use GPR for humanitarian demining; however, there are not many successful examples. ALIS is a hand-held GPR developed for humanitarian demining activities by Tohoku University (Sato et al., 2012, 2007). We started the development of ALIS in 2002 and the prototype of ALIS was tested in Afghanistan in 2004. Then ALIS has been tested in a few mine affected countries including Egypt and Croatia. Figure 1 shows the ALIS system and Fig. 2 shows an example of GPR image obtained by ALIS.

ALIS is a dual sensor, which combines a metal detector (electromagnetic induction sensor: EMI) with GPR. A metal detector is widely used in land mine detection, however, there are too many metal fragments, and GPR is used for classification of buried objects detected by a metal detector. The soil in mine fields is very inhomogeneous, which contains much gravels and tree roots. Therefore, radar signal clutter from these objects is very strong and it makes the landmine detection by GPR difficult. ALIS is equipped with a CCD camera, which acquires the ground surface image 4–5 times every second, and we estimate the relative movement of the antenna position. With this antenna position information, GPR signal can be used for SAR processing. Figure 2a shows the SAR processed image at 10 cm in depth and the trajectory of antenna scanning, while Fig. 2b is the raw GPR data sets (time slice) at that time. The operation frequency of ALIS is 500 MHz–3 GHz and the center frequency is at about 2 GHz, whose wavelength in soil is about 5 cm, and the sampling spacing is about 1–5 cm. We can find that the SAR processing provides much better image, and at the same time, clutter was drastically reduced by SAR processing.

We found that, we can obtain a good image from the relatively sparse data acquisition by using ALIS. The SAR/migration processing is very effective tool for imaging and without the signal processing, it is almost impossible to detect buried mines in real mine field soil conditions as shown in Fig. 2b.

Since 2009, we have an ALIS team, which operates 2 sets...
of ALIS systems by 4 Cambodian deminers, in the Cambodian Mine Action Centre (CMAC), which is a governmental organization for mine clearance in Cambodia, and ALIS has detected more than 80 min, and the deployment by CMAC is continuing.

2.2 Applications to Disaster Monitoring and Archaeology

Although we believe migration/SAR processing is very useful for high resolution image reconstruction in GPR, there are some limitations or differences between space-borne SAR and GPR. Therefore we also have investigated another approach, namely “3D GPR”. 3D GPR, which has been developed by Grasmueck and Viggiano (2007), is virtual realization of high-accurate position controlling of the GPR system. We interpolate the GPR signal from very densely acquired data with high-positioning information. The data is typically acquired every 1 cm along the survey line, and separation of parallel survey lines is about 15–20 cm, and very dense 2-dimensional GPR data is acquired in 3D GPR system. The data acquisition position is randomly distributed, but from the very dense data sets, we can interpolate the GPR data on the “virtual” rectangular grid points. The regularly arranged GPR data shows a fine resolution 3-dimensional GPR image. We can also apply migration to these data sets.

We have applied 3D GPR measurements for many purposes, which include disaster mitigation, archaeological survey and facility detection. Figure 3 shows the measurement in one of the archaeological survey, which we have conducted at Sai-tobaru, Miyazaki, Japan (Sato et al., 2010). There is a grave in this site. Figure 4 shows the 3D image which was obtained by interpolation and 3D migration. We could very clearly image the shape of the subsurface cave, and could find some buried objects, which are made of metal. Before our 3D GPR survey, the site was investigated by conventional GPR survey, but such a detailed information or image could not be obtained, and only anomaly could be found at the site.

After 3.11 East Japan Great Earthquake and Tsunami in 2011, we were contacted by the local government of Iwaki City, Fukushima, which is located about 50 km from the Fukushima-Daiichi nuclear power plant. Many small scale subsurface coal mining have been carried out until 1960s in this area. Many of the subsurface facilities have been abandoned by 1970s, and even the locations of these facilities are unknown now.

In some sites in this area, we found anomalous water coming up to the ground surface and local people were afraid that the phenomena are related to corruption of subsurface mine facilities. We then have conducted 3D GPR survey in these sites. We could find some voids, and water paths in these sites as shown in Fig. 5, and could confirm the existence of the voids by drilling. We think this kind of surveys have to be continued to avoid any further accidents induced by the mining activities.

3 ARRAY GPR “YAKUMO”

Although this 3D GPR can provide us very accurate subsurface images, unfortunately, the data acquisition takes significant amount of time, because the data acquisition density is very high. We are continuing research to reduce the data acqui-
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Figure 5. 3D imaged subsurface void, in Fukushima, Japan.

One of the approaches to realize this is array GPR. Conventional GPR uses an antenna system which is composed of one transmitter and one receiver. Two-dimensional data acquisition by one pair of antennas is slow, and the spacing of antenna survey lines is irregular and it provides us poor quality 3D images. Therefore advanced SAR processing or signal processing techniques have to be employed. One of the ways to solve this problem is an array GPR. We are now developing an array GPR system “Yakumo” which means 8 rising clouds in Japanese.

Figure 6a shows the array GPR system “Yakumo”. It was designed to be scanned by hand, or pulled by a small vehicle. There will be almost no chance the system can be pulled by a larger car, because the survey area in Japan is normally not very large and not flat. Yakumo is a stepped frequency continuous wave (SFCW) system, operating at 50 MHz–1.5 GHz. We have designed a system having 8 transmitting antennas and 8 receiving antennas, and by switching we can acquire all 64 pairs for each combination of transmitter and receiver as shown in Fig. 6b.

In the signal processing for Yakumo, we can use the multi-static SAR processing shown in (2), and we can use wide incident angles for imaging one subsurface position. Yakumo has been used for many practical applications, mostly in very wide areas. One of the most useful applications is the surveying of remaining objects flushed by the Tsunami, which attacked East Japan on March 11th, 2011. Tohoku University is located in Sendai, which is about 150 km from the epicenter of this gigantic earthquake, and more than 15 000 people were killed by Tsunami. After 3 years of the hazard, still more than 2 000 people are missing. We used Yakumo on several sand beaches, where we have many Tsunami victims. Local police is still surveying any remaining objects, but they can survey only on the ground surface. By using Yakumo, we found many objects that were buried between 50 cm and 1 m, which were apparently wave flushed and buried in the sand by the Tsunami.

Figure 7 shows an example of a horizontal slice GPR image acquired by Yakumo, where buried objects in sand can be found. Typically, 50 m by 100 m rectangular area is surveyed by Yakomo, and the data acquisition takes about 1 hour and data processing takes about half an hour. This is drastically faster compared to a conventional GPR survey.

In addition to the conventional GPR survey, using the unique multi-static properties of Yakumo, we can use Yakumo data for CMP signal processing. If we select antenna pairs, whose connecting paths crosses the common CMP point, we can use the data sets for CMP processing. A very important advantage of using Yakumo for CMP data processing is that we can acquire the data at one time, and we do not have to repeat measurement for CMP data acquisition. Using this technique, we can estimate the vertical profile of the dielectric constant, which can be used for SAR processing.
Figure 7. Horizontal slice GPR image acquired by Yakumo. Buried objects in sand dune can be found.

4 GB-SAR: GROUND-BASED SYNTHETIC APERTURE RADAR

Ground base synthetic aperture radar (GB-SAR) is one form of synthetic aperture radar (SAR), which is now becoming popular, but its concept and signal processing are very similar to what we have used for GPR. Most of the SAR sensors are mounted on space crafts or airplanes, because SAR data have to be acquired along a very long survey line, so that SAR processed data will have a high azimuth resolution. However, such space-borne or airborne SAR cannot acquire data continuously at one fixed position. GB-SAR is a SAR system which is operated on a fixed rail. The SAR antenna moves on a fixed rail repeatedly, and can obtain SAR images regularly. GB-SAR can acquire SAR images only in a fixed area, and due to the limited length of the survey line, the resolution is also limited, but it has many advantages compared to conventional space-borne or airborne SAR system.

4.1 Ground Slide Monitoring

Observation of landslides is one of most typical applications of GB-SAR. Conventionally, discrete sensors such as GPS or tension sensors have been used to monitor landslide, but information on discrete points on a slope may miss the critical deformation of the ground surface. GB-SAR can acquire 2D data on a slope with one system, and can detect small ground surface deformation by interferometry.

We are deploying a GB-SAR system working at 17 GHz at Aratozawa Landslide site, Miyagi, Japan since 2011. Figure 8a shows our system, and Fig. 8b is an interferometric SAR image, which visualizes the ground surface fall by a small scale earthquake.

4.2 Inspection of Inner Structure of Wooden Houses

GB-SAR system can be used for imaging near range targets. One of our recent research targets is imaging inner structure of wooden buildings. Many of Japanese private houses are made from wooden structure. Wooden construction is flexible and can resist against a strong shake due to earthquakes. If the concrete structure is deformed by a strong earthquake, cracks inside the concrete may be caused, but due to elastic properties of the wooden structure, it can absorb the deformation. However, if the deformation exceeds the limitation, the wooden structures may be damaged. In some cases, they cannot be observed from the outside, because the structure is covered by a wall, which is also elastic.

We think that GB-SAR and subsurface radar have great potential as a non-destructive inspection method for wooden structures. Figure 9 shows an example of a GB-SAR measurement which we are conducting. A GB-SAR system which operates 10–20 GHz was used for imaging inside structure of a wooden wall model. We could demonstrate that the wide frequency system has a very high resolution, and a polarimetric system can visualize a very small deformation of the structure. For example, we can see the detailed structure inside the wall.
in Fig. 9c. It shows the vertical and horizontal wooden pillars, and inclined section of the wooden plate. This inclined part of the wooden structure was damaged by pressing the wall structure beforehand to imitate the damaged wall structure. In Fig. 9d, we can observe that the color of this part is not uniform. This color indicate the phase differences between the vertical and the horizontal polarization, and we think this polarimetric information can visualize the detailed structure, which cannot be observed by the reflection intensity images.

Figure 9. GB-SAR applied to nondestructive inspection of wooden building. (a) A model of a wooden wall with GB-SAR system; (b) inner structure of the wooden wall; (c) GB-SAR intensity image of the wall model; (d) polarimetric GB-SAR image of the wall model.

5 CONCLUSION

In this paper, we demonstrated applications of near range radar systems which include GPR and GB-SAR. High resolution imaging by SAR processing is one of the key technology, however, polarimetric and interferometric processing and data interpretation can expand their possibilities. We show the GPR used for detection of buried mines. The new sensor ALIS, which was developed by our group, demonstrates that imaging by migration can clearly visualize the buried land mines under the very strong clutter conditions. Then we show that 3D GPR can visualize the detailed structure of subsurface grave. Very dense GPR data sets can be used for high quality image reconstruction, but the array GPR can be used for the fast data acquisition, keeping the quality of the images. We developed an array GPR “Yakumo” and demonstrated that it can acquire the data in the area of 100 m by 50 m in one hour. Then we discussed GB-SAR using two examples. The first example is application to landslide monitoring. The area of 400 m wide and 100 m high can be observed by one radar system, and the deformation of the ground surface can be detected very accurately. The second example is application to non-destructive observation of wall structures. The polarimetric radar image can show very small deformation of structures.

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