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 geoenvironmental surveys 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

\[ u(x, y) = \int d(x', t) \frac{2R(x', y) \cdot d(x', y)}{v} \text{d}x' \]  

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

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

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