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Fundamental Study on NDT of Building Wall Structure by Radar

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ABSTRACT

GB-SAR (Ground Based Synthetic Aperture Radar) for inspection of wooden and concrete walls and structures has been developed and the system was evaluated by test measurements. The GB-SAR system uses frequency bandwidth 1-10GHz, and it can acquire full polarimetric radar signal. Then Synthetic Aperture (SAR) Radar signal processing is used to reconstruct 3-dimensional images of inner structure of the targets. We found that the radar polarimetry gives us very precise information of the damaged structures, and demonstrated that radar polarimetry is a useful tool for detecting fractures inside a concrete structures, and detection of small deformation of wooden structures.

KEYWORDS : *GB-SAR, radar polarimetry, Wooden structure, Concrete structure, NDI.*

INTRODUCTION

Subsurface radar including Ground Penetrating Radar (GPR) has gathered interest as a method to observe and detect anomalies beyond the surface. One of the applications is the through wall radar, where the main objective is detection of moving targets behind the wall. We have investigated a monitoring method of static targets beyond the surface of objects by Synthetic Aperture Radar (SAR) technology for high resolution imaging. In particular, if the radar antennas are away from the surface of the objects, but set on a fixed position, we refer the system as Ground-Based SAR (GB-SAR).

The demand to inspect the structure of building walls is growing since there are a thousand of potentially damaged buildings in Japan due to the 3.11 Earthquake and Tsunami. Typically in tsunami affected areas, we can find houses standing normally, but the inner structure of the houses are completely damaged. The ministry of internal affairs and communication of Japan started an intensive research project to develop the Non-destructive testing (NDT) methodologies for evaluation of the damage of wooden houses. This kind of technology will also be applied to concrete structures and buildings, however, many of the private houses in Japan is made of wood. Damages on buildings are sometimes obvious from the outside; however, in many cases, damages are hidden inside the structures of walls, and they cannot be found from outside. A common way of the inspection is to remove the material of the wall and visually inspect the inner structure. However, this technique damages the building and cannot be applied to many private houses.

In order to assess damages inside wall of structures in non-destructive manner, radar systems, typically GPR are commercially available. The largest issue of radar for nondestructive building inspection is the resolution. In order to achieve the higher resolution, we use SAR algorithm for image reconstruction. Higher frequencies are preferred to detect small defects in walls, because we can have a larger frequency bandwidth; however, a large part of energy at higher frequencies is reflected at the surface and/or is attenuated in the material. To overcome the problem in this study, radar polarimetry is applied, which has been validated to bring detailed information on targets in remote sensing.

In this paper, some results of the feasibility study are shown in order to demonstrate that radar polarimetry can be useful for these purposes.

1 GB-SAR SYSTEM

For the study, a polarimetric radar system is constructed based on a vector network analyser (VNA). Transmitting and receiving antennas are connected to the VNA to consist a radar system. VNA is used for transmitter and receiver, because the system is very flexible, and the operation frequency can be selected. One of the important features of the GB-SAR system is radar polarimetry. In order to have higher resolution of radar image, we have to have very wide frequency range for improving the range resolution, and wider scanning length should be used for higher azimuth resolution. However, even if we try to have higher resolution, it is not easy to observe very small detailed of the structures. Radar polarimetry is a technique which can overcome this problem.

1.1 Antennas for Polarimetric Measusremet

In order to achieve, a wide-frequency range and full polarimetric radar data acquisition, we are using 2 antenna types, namely Vivaldi antenna and Spiral antenna. Both these antennas are known as wide frequency range operation, but Vivaldi antenna is for linear polarization, and Spiral antenna is for circular polarization.

Vivaldi antenna as shown in Fig. 1 is used for liner polarisation, because antenna has a very good performance from 1GHz up to 20GHz. 4 antennas and combined as an array as shown in Fig.1, where 2 are for Horizontal and Vertical transmitter and 2 are for Horizontal and Vertical receiver. This array configuration is used to achieve full-polarimetric radar data acquisition in liner polarization, however, isolation between antennas are not very high, and additional signal processing to reduce the antenna coupling is required.

Spiral antennas as shown in Fig.2 is used for circular polarization. Electromagnetic absorber is attached behind the antenna elements to supress the radiation and reception from the behind. Four spiral antennas are fabricated with left and right circular polarisation aligning as a two by two matrix so that full polarimetric measurements can be accomplished by switching active antenna combinations. The diameter of the antennas is 90 mm and the dominant frequency is about 3 GHz.

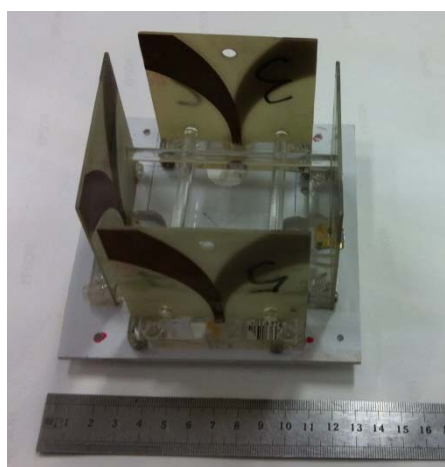


Figure 1: Vivaldi antenna

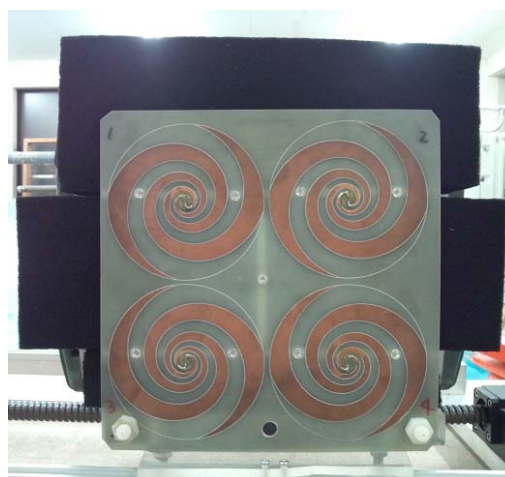


Figure 2: Spiral antenna



Figure 3: Setup of antenna son a antenna positioner

Table 1: GB-SAR System Specification.

Items	Specification
Antenna	Vivaldi or Spiral
Frequency	1-20GHz
Polarization	HH/VV/HV/VH or RR/RL/LR/LL
Antenna position step	1cm
Scanning area	1m x 1m

1.2 Polarimetric Analysis

Radar polarimetry is a radar signal processing technique which is commonly used in SAR acquired by airborne or spaceborne SAR systems. Radar polarimetric analysis is based on the electromagnetic wave scattering mechanism from the radar targets, and we can retrieve physical information of the targets, which is not only the shape information. SAR has always suffered from the limited bandwidth of the operation frequency, which determines the radar range resolution. We think radar polarimetry is one of the very promising techniques which can overcome the problems caused by limited radar image resolution.

In radar polarimetry, we define the scattering matrix \mathbf{S} of radar target as:

$$\begin{bmatrix} E_x^s \\ E_y^s \end{bmatrix} = \mathbf{S}(x, y) \begin{bmatrix} E_x^i \\ E_y^i \end{bmatrix} = \begin{bmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{bmatrix} \begin{bmatrix} E_x^i \\ E_y^i \end{bmatrix} \quad (1)$$

where $\begin{bmatrix} E_x^i, E_y^i \end{bmatrix}^T$ and $\begin{bmatrix} E_x^s, E_y^s \end{bmatrix}^T$ are x and y component of incident and scattered electric field to the targets, which can be acquired by a radar system which is consist from orthogonal polarization transmitting and receiving antennas. The scattering matrix in (1) is defined for linear polarization having the x and y components. However, it is well known that if we have full-polarimetric data sets, scattering matrix for arbitrary polarization vases can be mathematically obtained. For example, the scattering matrix for circular polarization can be obtained from (1) as :

$$\mathbf{S}(LR) = \begin{bmatrix} S_{LL} & S_{LR} \\ S_{RL} & S_{RR} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \begin{bmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{bmatrix} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \quad (2)$$

1.3 Image reconstruction

We will use Synthetic Aperture Radar (SAR) processing for reconstruction of the inner structure images of the targets. Since the distance from the antennas to the imaging point is very close, we cannot use the FFT algorithm which is common in SAR signal processing. In addition, the position differences of the transmitting and receiving antennas have to be considered. The bistatic radar SAR processing algorithm for image reconstruction is given as:

$$u(x, y, z) = \iint f\left(t - \frac{2R(x, y, z, x_t, y_t, z_t, x_r, y_r, z_r)}{c}\right) dx_r dy_r. \tag{3}$$

$$R(x, y, z, x_t, y_t, z_t, x_r, y_r, z_r) = \sqrt{(x_t - x)^2 + (y_t - y)^2 + z_t^2} + \sqrt{(x_r - x)^2 + (y_r - y)^2 + z_r^2} \tag{4}$$

where $u(x, y, z)$ is the reconstructed 3-dimensional image, $f(t)$ is the acquired radar signal when the position of the transmitting and receiving antennas are and (x_t, y_t, z_t) , (x_r, y_r, z_r) and c is the velocity of light.

2 CONCRETE STRUCTURE

The GB-SAR system was evaluated at first by using a concrete specimen, which simulates one span of a concrete wall structure. The specimen used for this test was artificially pressed and deformed, which caused apparent fracture inside and outside the concrete structure as shown in Fig.4. We used spiral antennas and carried out measurements with 2-dimensional scanning. The scanning was repeated three times with different combinations of polarization, i.e., LL, RR, and LR.

We reconstructed 3-dimensional image from the measured data in the circular polarization basis by using SAR processing given in (3), and the reconstructed images are shown in Fig.5.



Figure 4: Concrete wall measurement setup.

Then the circular polarization image was transformed to the linear polarization images, i.e., HH, VV and HV by using (2). The obtained radar image shown in Fig. 6 in the HH polarization shows an only horizontally placed rebars and VV shows only vertical one. Once we obtained the full-polarimetric radar data sets, we can transform the radar image in any polarization status. As we could see in Figs. 5 and 6, radar image can be changed by changing the polarization status. We can use these phenomena to detect some specific targets from radar images, which are known as polarization optimization or polarization filtering method. We think concrete surface, rebars and cracks inside concrete structure could be separated by this polarization filtering.

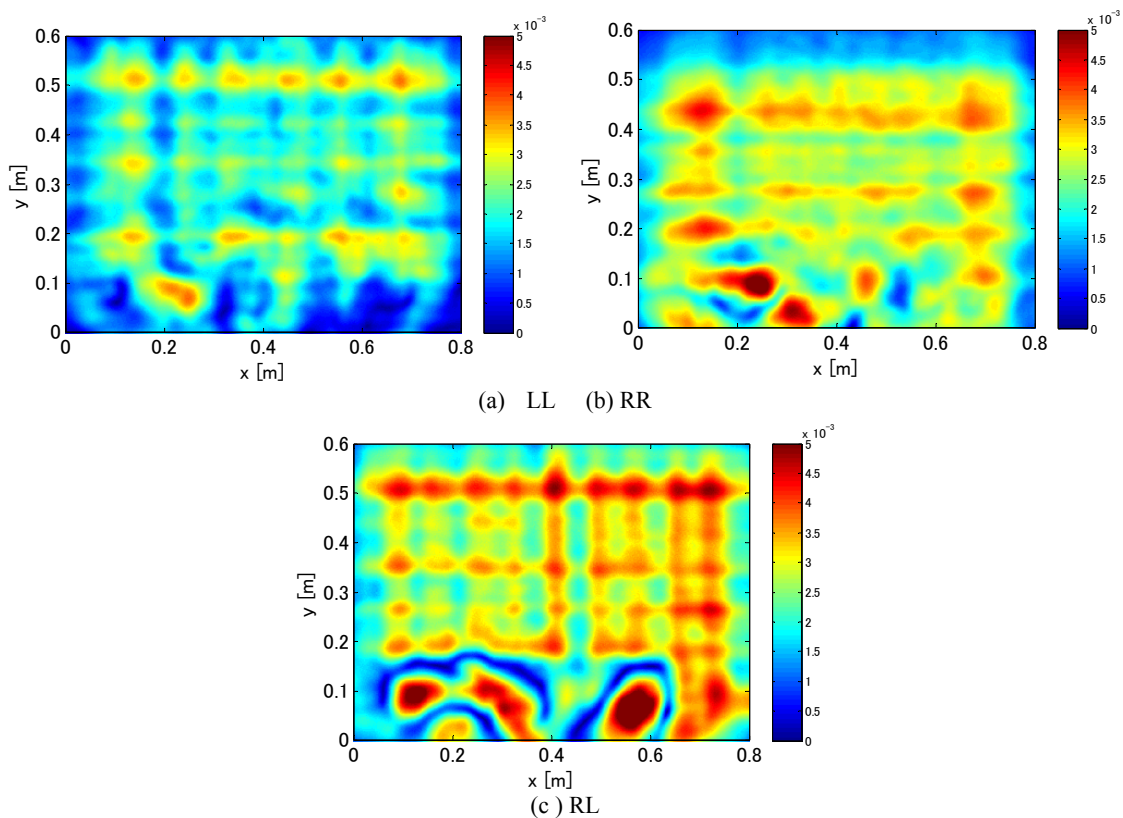


Figure 5: Reconstructed radar image based on circular polarization (depth of 16.5 cm).

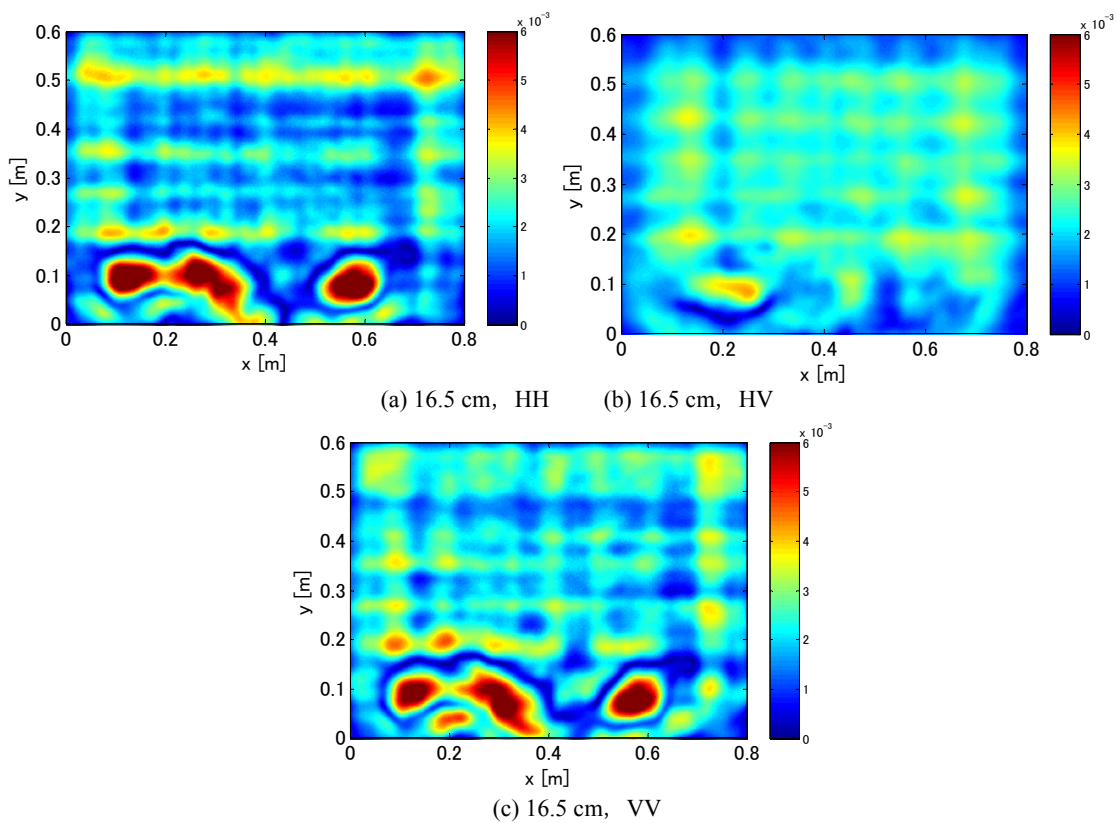


Figure 6: Reconstructed radar image based on linear polarization (depth of 16.5 cm).

3 WOODEN STRUCTURE

Many of private houses in Japan are made of wooden structure. Due the frequent earthquakes in Japan, we have improved regulations for constructing wooden houses after 1981. We had Hanshin-Awaji earthquake in 1995 and then the regulation was again changed. Fig.7 shows the one span of a wall of a typical wooden house, which is constructed the regulation after 1995. Note that due to the limitation of the height of the room, the wooden specimen is rotated by 90 degree. We made 2 specimens for each type, and one of the specimens was deformed by pressing by jack and the inner structure was damaged. We cannot find the damage from outside as seen in Fig.7.



Figure 7: Wooden wall model specimens set in a laboratory room.

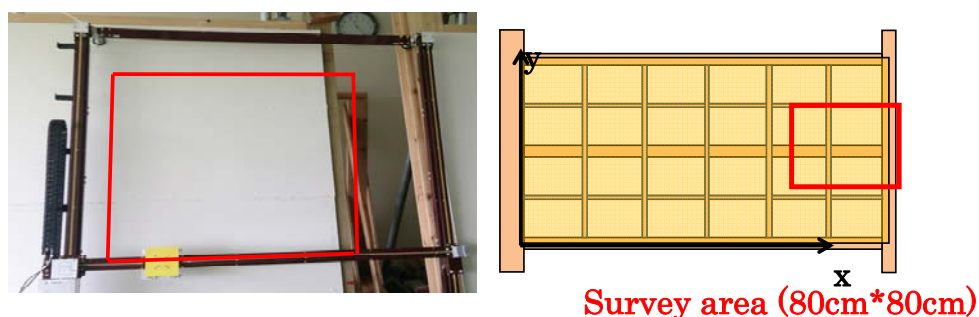


Figure 8: Wooden wall model made after the regulation after 1995 and the radar survey area

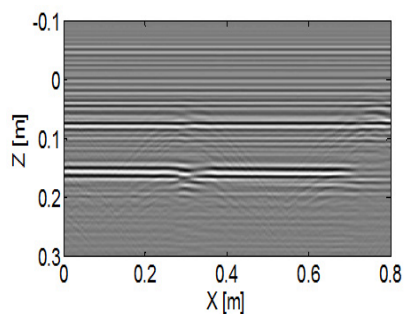


Figure 9: Raw radar profile (Vertical section)

Radar data was acquired by using Vivaldi antennas for these wooden structures. Fig.9 shows the raw radar signal which shows the vertical section of the wooden specimen. We can find several reflecting objects, but the shape of the inner structure is not very clear in the raw radar signal. Fig.10 shows the reconstructed radar image by SAR processing. Comparing the vertical radar profiles in Figs 9 and 10(a), we can understand that the SAR processing clearly shows the structure of the target, and suppress the diffracted radar signal. In addition, we can find this high resolution shape of the metal objects such as the head of nails in Fig.10(b). We think that the detection of the deformed metal objects used for joining the wooden structure can be a good indication of damage to the structure.

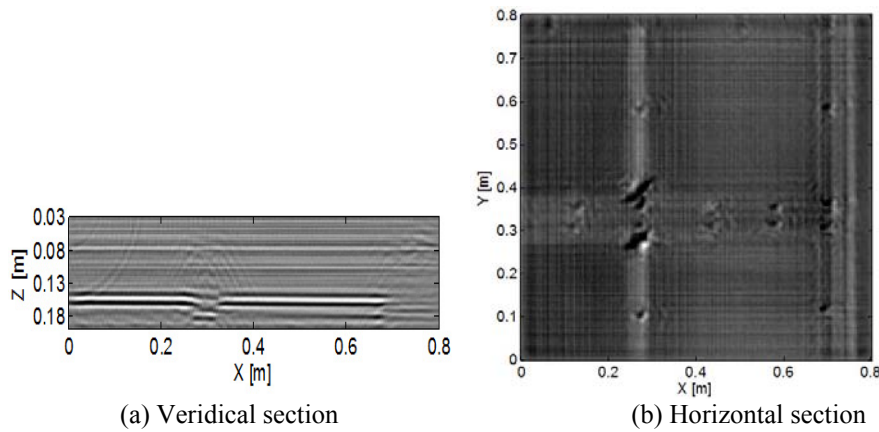


Figure 10: Reconstructed image of inner structure of wooden wall model by SAR processing



(a) Inner structure of the model under the regulation before 1995.
Amplitude ($d=1.5\text{cm}$)

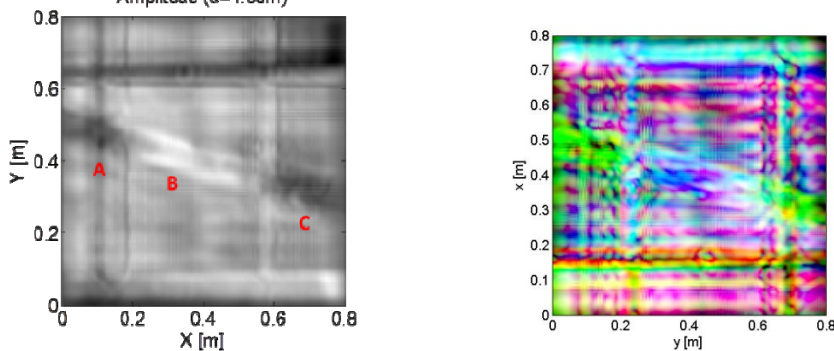


Figure 11: Reconstructed image of wooden structure.

Fig.11(a) shows the intensity of the reconstructed SAR image, and Fig.11(b) shows the phase differences between the polarization. Fig.11 (b) shows that the part of the inclined wooden bar was

deformed by pressing the wall structure by its intensity contrast, but Fig.11(c) shows more clear damage to the structure. We think that radar polarimetry approach is very sensitive in detection of the deformed structure.

CONCLUSION

We have developed a wide-frequency band full polarimetric GB-SAR system, which operates at 1-20GHz. We have demonstrated some measured results. For a concrete structure we found that by polarization optimization, we can separate the images of concrete surface, rebars and cracks inside the concrete structure. For the measurement of a wooden wall model, we demonstrated that we can image small metal parts inside the structure, which will be useful information for understanding the history of the damage, and also showed that radar polarimetry can detect small deformation of wooden structure which is less than 5mm.

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