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Time-frequency spectral analysis of step frequency continuous wave and impulse ground penetrating radar

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***Abstract*— Time-frequency spectral responses of an in-house built step-frequency continuous wave (SFCW) GPR (Yakumo) developed by Tohoku University and a commercial impulse GPR were studied and compared. The Yakumo SFCW GPR operates from 50MHz to 1.5GHz, and the center frequency of the commercial impulse GPR is 500MHz. Both GPRs were probed on top of an embedded steel pipe overlaid by a concrete pavement. The time domain radargram signals were transformed to time-frequency domain through continuous wavelet transform with Morlet wavelet as the mother wavelet. The study reveals, with a definite buried pipe as a reflector, how the spectral responses in both frequency domain and time-frequency domain are changed by two different bandwidths and two different ray paths of the GPR wave propagation into materials.**

***Index Terms*—ground penetrating radar, impulse radar, step frequency continuous wave (SFCW), wavelet transform**

I. Introduction

Commercial impulse ground penetrating radar (GPR) has been commonly used for engineering, archaeological and geological projects, for its ability in locating underground object and imaging subsurface environment. To fit different requirements of depth and resolution as a trade-off of one another, pulse antenna with a fixed center antenna frequency is normally used. When depth and size of target objects are not roughly known, such fixed use of pulse antenna frequency can be a major restriction of subsurface mapping. To overcome this weakness of traditional pulse GPR, step frequency continuous wave (SFCW) GPR, making use of a wide range of frequency in one pulse encompasses, is introduced and, is surely one of the most popular research topics in recent years.

Signals of the pulse and SFCW GPRs were studied and compared in this paper. The commercial MALÅ 500 MHz pulse radar was employed , whereas Yakumo is an in-house SFCW GPR system developed by Tohoku University. The two systems have distinct features in terms of frequency ranges, data collection modes and types of frequency signal. The commercial radar is of center frequency 500MHz and emits impulse frequency signal, and the data are collected in time domain. In contrast, Yakumo transmits step frequency signal, its frequency range lies between 50MHz and 1.5GHz, and the frequency step size is 5.66 MHz over the whole spectrum (Fig. 1) [1]. The data collected by Yakumo are in frequency domain and the instrument deploys synthetic aperture radar (SAR) technology to process the data. In terms of hardware, the Yakumo system is a multi-static array GPR which composes of 8 transmitting antennas (Tx) and 8 receiving antennas (Rx), data from 64 channels are acquired for each survey line [1] (Fig. 2). Yakumo has been used in many archaeological projects and detection of buried objects in Northeast Japan after the strike of tsunami which occurred subsequently after the Great East Japan Earthquake in 2011.

In this paper, the spectral responses of a buried steel pipe measured by the two systems were studied and compared in frequency domain and time-frequency domain, in order to observe how the bandwidth and ray paths contribute to the differences in the non-stationary GPR signals.

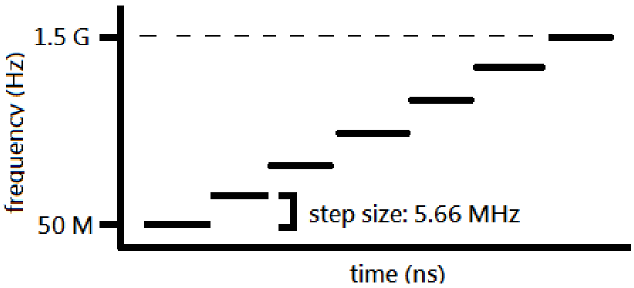

Fig. 1 Waveform of Yakumo.

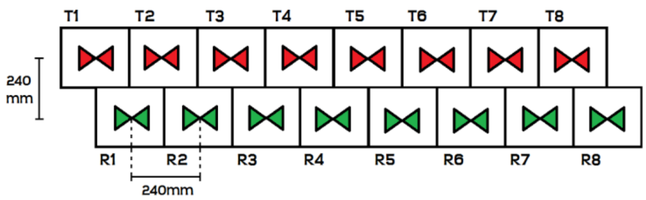

Fig. 2 Structure of Yakumo in plan view. The antennas in red are the transmitting antennas and the antennas in green are the receiving antennas.

II. DATA COLLECTION

Fig. 3 Survey site with embedded steel pipe and the Yakumo is the large white instrument at the left bottom.

The survey area consists of a steel pipe sized 10 cm in diameter buried in dry sandy soil with concrete pavement at 0.8 m depth. MALÅ 500 MHz antenna with ProEx control unit and the in-house Yakumo antenna were deployed to measure a grid of 4 x 5 m^2 (Fig. 3).

Data of antenna in air was also acquired to be used as reference data. Air is a suitable medium for acquiring reference data as it is not dispersive in nature, therefore it provides a stable medium for collecting reference data.

III. SIGNAL PROCESSING

A. Processing in time domain

To preserve the authenticity of the dispersive spectral content evolving with time/depth axis, processing procedures were only applied where necessary, and the processing steps are different for frequency domain and time-frequency domain analysis.

Basic processing like removal of direct current (DC) shift, dewow filter and time-zero correction were applied. DC shift eliminates DC bias in the signal and the dewow filter filters the very low frequency noise [2]. As for time-frequency domain analysis, the processing procedures are summarized in Table I. Exponential gain control was used to overcome the weak reflected signal of the pipe when compare to the strong direct wave. The scaling factor of the gain curve is carefully adjusted to mitigate the distortion of amplitude information. The purpose of applying background removal was to remove the ringing noise being observed in Yakumo. Since it is a 2D filter, the effect to frequency information is minimal. After performing these processing procedures, the processed data were then analyzed in frequency domain and time-frequency domain.

B. Processing in frequency domain

After processing of data in time domain, Fourier transform was applied to convert the data from time domain into frequencies, all the data were then normalized and plotted in graph for analysis as depicted in Fig. 5 & Fig. 6.

Normalization of amplitude was performed by dividing amplitude of each frequency point by the maximum amplitude of the respective frequency spectrum, which means that the spectrum shown in Fig. 5 and Fig. 6 are displaying ratio information. The normalized amplitude (where the amplitude was cut off at unity) can be interpreted more effectively to reveal the weak signals in later time window.

C. Processing in time-frequency domain

Time-frequency domain is able to express two types of information in one single plot, which makes it easier for data interpretation as the evolving and dispersive frequency content of the non-stationary GPR signals is correlated to the time axis. The plot can be produced by transforming the A-scans into a frequency map where the x-axis and y-axis represent the time and frequency respectively, and hence, the frequency distribution is spatially expressed across time[3].

Wavelet transform was used in the time-frequency domain, and the algorithm is described in the following section. Advantages of which are reported in Lai et al. [3].

1) Wavelet transform (WT)

WT decomposes a wave into a family of wavelets, and the wavelet are dilated and translated with the scale and shift factor respectively as shown in Eq. 1 [3].

Integral continuous form $WT_{u,a} = \langle s, \Psi_{u,a} \rangle$

$$= \int_{-\infty}^{\infty} s(t) \Psi_{u,a}^{*}(t) dt$$

where mother wavelet $\Psi_{u,a} = \frac{1}{\sqrt{a}} \Psi\left(\frac{t-u}{a}\right)$

(1)

TABLE I. Summary of processing procedures in time domain for spectral analysis

Processing procedures \ Data	MALÅ 500 MHz antenna in air	MALÅ 500 MHz antenna on soil with buried pipe	Yakumo in air	Yakumo on soil with buried pipe
DC shift removal	✓	✓	✓	✓
Dewow	✓	✓	✓	✓
Exponential gain control	✗	✓	✗	✓
Time zero correction	✓	✓	✓	✓
Background Removal	✗	✓	✗	✓

In this case, mother wavelet is a complex-valued Morlet wavelet, u is the shift factor and a is the scale factor of a wavelet.

Since the window size is not fixed, the dilation and translation are dependent on the frequency and governed by the mother wavelet [3]. Such versatile nature of WT allows multi-resolution analysis (MRA) of a signal, as depicted in Fig. 4.

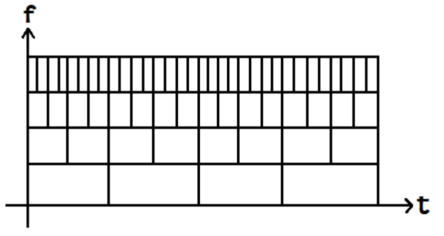

Fig. 4 Time resolution is finer at higher frequency, vice versa.

The time resolution and frequency resolution are decided by the time window and bandwidth respectively, and the two resolutions are inversely proportional, consequently, a wavelet with longer time duration, like direct wave, has finer frequency resolution, and the fine time resolution of wavelets with small scale factor allows the detection of transient and abrupt high frequency components (e.g. reflector) at later time window with a distinct time/distance away from the direct wave [3].

Analysis of these frequencies can be expressed in the form of 2D frequency maps that shows the distribution of energy of individual frequency over a spectrum as y-axis and time step as x-axis, in which the amplitudes ($WT_{u,a}$) are calculated using Eq. 1 and plotted with time scale [3].

IV. FINDINGS AND DISCUSSION

A. Frequency domain

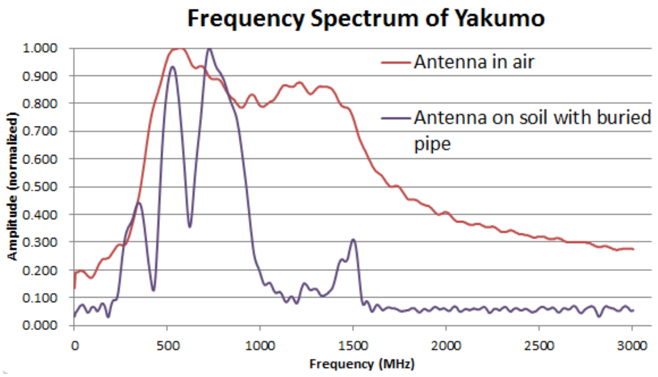

Fig. 5. Overall frequency spectrum of Yakumo.

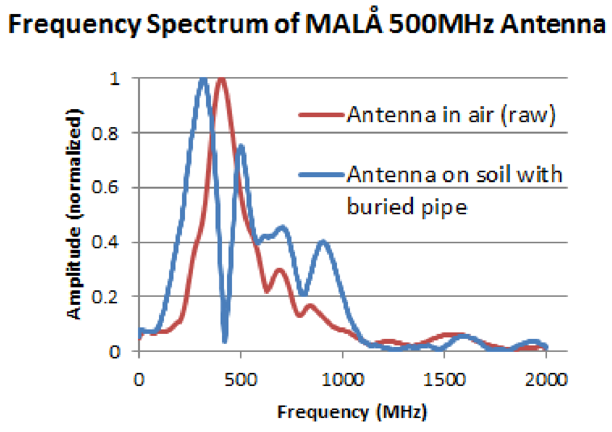

Fig. 6. Overall frequency spectrum of MALÅ 500 MHz antenna.

The data of antenna on soil with embedded pipe and antenna in air were compared for both GPRs. From Fig. 5, a wide and relatively flat frequency spectrum which covers most of the claimed operating frequency range (50MHz to 1.5GHz) of the Yakumo system can be observed, and a considerable amount of higher frequency components are absorbed when the antenna is on soil with embedded pipe due to absorption of high-frequency energy by host material [4]. In contrast, as depicted in Fig. 6, the 500 MHz antenna shows a conical downward penetration with frequency spectrum which concentrates at 500 MHz and absorption as in Yakumo.

The observations are as expected for the respective antennas. Impulse radiating antenna is a kind of "focused aperture ultra-wideband (UWB) antenna" [5], and it radiates very short EM pulses when a waveform with rapid rise time step with a time base of nano-second is created. The shape of frequency response is conical or narrow because the traverse electromagnetic (TEM) feed structure is composed in a conical and non-dispersive shape (Fig. 7) [5].

SFCW radar is a synthesized system, in which a series of individual frequencies in impulse waveform with known amplitude and phase is synthesized sequentially [5], or in other words, a continuous sinusoidal wave which changes its frequency sequentially, it can be expressed mathematically in Eq. 2 [6].

$$f(t) = A \ exp[j2\pi(f_1 + n\Delta F)t]$$
$$\text{for } \frac{n-1}{N}T \le t < \frac{n}{N}T; 0 \le n \le N-1$$
(2)

where A is the signal amplitude, T is the signal period, N is the total number of frequency steps and ΔF is the frequency step size.

B. Time-frequency domain

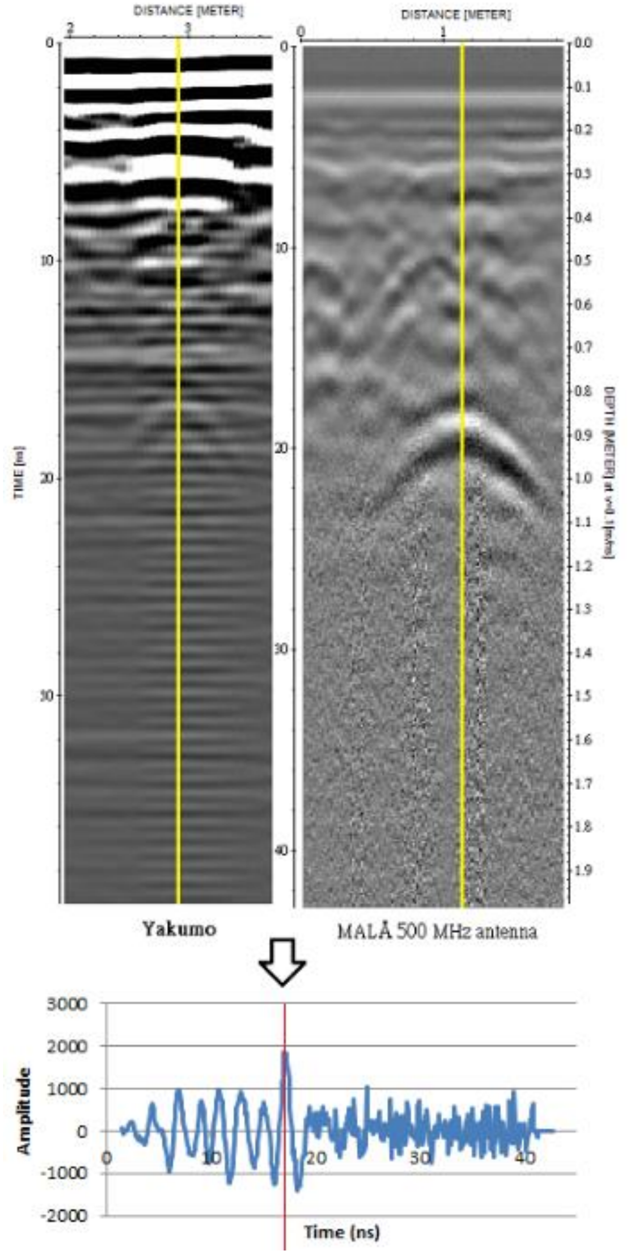

Fig. 7 The A-scan which contains the peak of the hyperbola was extracted from the two B-scans respectively, and the selected trace was then processed with WT to produce the frequency maps

Fig. 9 and Fig. 10 show the time-frequency maps of the A-scan which is directly on top of the buried pipe in the time-frequency domain.

For the Yakumo system, overwhelming ringing noise is observed at 1.5 GHz in Fig. 10. By taking this information into account and eliminating the ringing noise, the frequency response of the reflector is said to be about 600 MHz with reference to its position in the time axis at around 17 ns, as depicted in Fig. 10a & b. For the MALÅ 500 MHz antenna, the frequency response of the pipe is concentrated at 400 MHz at 17 ns (Fig. 9a). From Figure 10a & b, we can also observe that the amplitude of the pipe is greater than that in Fig. 9a & b, which was measured by the impulse radar.

The findings show that the frequency response of Yakumo is higher than the 500 MHz antenna in this case.

Although both sets of data were processed with gain control, the amplitude of reflector measured by the 500 MHz antenna is still very weak (Fig. 9a). However, the amplitude of the reflected signal measured by Yakumo can be observed in the maps (Fig. 10a & b) even with the presence of ringing noise.

For most impulse radar, the ratio of bandwidth to center frequency is about 1:1 [2], which means, for an antenna with center frequency at 500 MHz, its bandwidth is around 500 MHz, where the antenna being used in this study fulfills this property. Such rule does not apply in SFCW radar as no center frequency is defined (Fig. 5), instead, the series of sinusoidal waves in impulse waveform has constantly high amplitude throughout most of the operating frequency range (i.e. 50 MHz to 1.5 GHz).

Attenuation of signal increases with increasing frequency [2], amplitude of signal decreases as attenuation occurs. This downside is particularly prominent in impulse radar as the high frequency components decreases when it is further away from the center frequency (Fig. 6). Such problem does not exist in SFCW radar. The high frequency of signal in SFCW radar was retained with later time window, which supports the flat spectrum over the step frequency range as shown in Fig. 1. With such advantage, the response of the reflector (i.e. the pipe) can be seen in the frequency map with the presence of strong ringing noise, to compensate attenuation and absorption of materials required in pulse radar system.

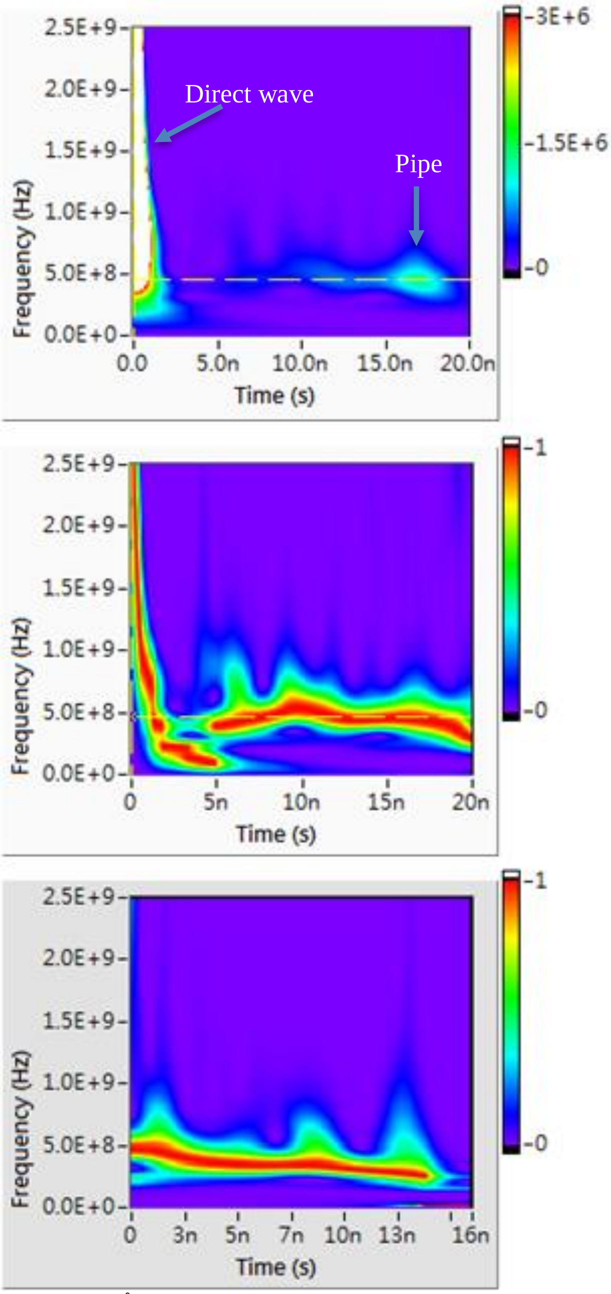

Fig. 9. MALÅ 500 MHz antenna (top) on soil with embedded pipe (absolute) (middle) on soil with embedded pipe (normalized) & (bottom) in air (normalized).

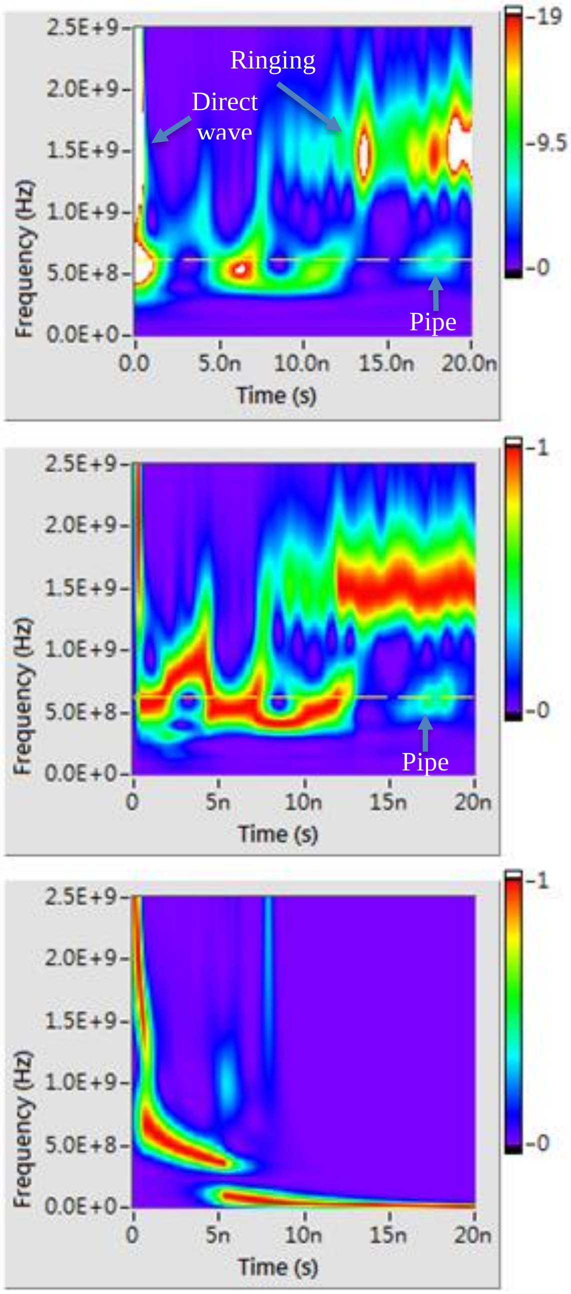

Fig. 10. Yakumo (top) on soil with embedded pipe (absolute) (middle) on soil with embedded pipe (normalized) & (bottom) in air (normalized)

V. CONCLUSION

From the above results and analysis, we can observe that SFCW radar and impulse radar differ from each other in terms of the shape of frequency spectrum and the amplitude and frequency response of reflector, in which the bandwidth and ray path contribute to the differences.

This paper has only studied and compared the signal analysis of the two systems in frequency domain and time-frequency domain on a known reflector, and there are more areas yet to be explored, such as how to improve imaging quality by observing the data in time-frequency domain, and filter at targeted time window to eliminate the ringing noise. The study of SFCW radar is not as popular as the impulse radar due to its complicatedness, therefore we hope that this paper can provide more insight of how SFCW radar behaves when compare to the conventional impulse radar and benefits further research in this area.

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