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FM-CW GPR and its Signal Processing

Pulse GPR (Ground Penetrating Radar) has been widely used in the field of archaeological prospecting recently; however, we have often encountered the limit of its applicability. So, the authors have developed another type ground penetrating radar, a FM-CW (Frequency-Modulated Continuous Wave) radar (Kamei *et al.* 1996). In the FM-CW radar, the transmitter frequency increases or decreases linearly with time. As the frequency cannot be continuously changed in one direction in practice, the transmitter frequency is triangularly modulated between 100 MHz and 500 MHz. The period of the triangle waveform is 50 m/sec. If there is a reflecting object at a distance R, the echo signal will return after a time $T=2R/v$ (where v is a velocity of electromagnetic wave in soil). If this echo signal is heterodyned with the transmitted signal, a beat signal will be produced. This beat frequency f_b is proportional to the delay time T; $f_b = aT$, where "a" is a rate of change of the transmitter frequency and a=16Hz/nsec in this case. Because the FM-CW radar is on the basis of detecting frequencies, the vertical axis of FM-CW radar profile becomes a frequency axis; furthermore, higher S/N-ratio is expected than pulse radar. And the FM-CW radar image is not affected so much by the "ringing", because the transmitted signal whose frequency spectrum is limited inside the bandwidth of antenna. Signal processing techniques play an important role in detecting frequencies from the beat signal and in making images in the FM-CW radar. In this paper, such techniques are discussed.

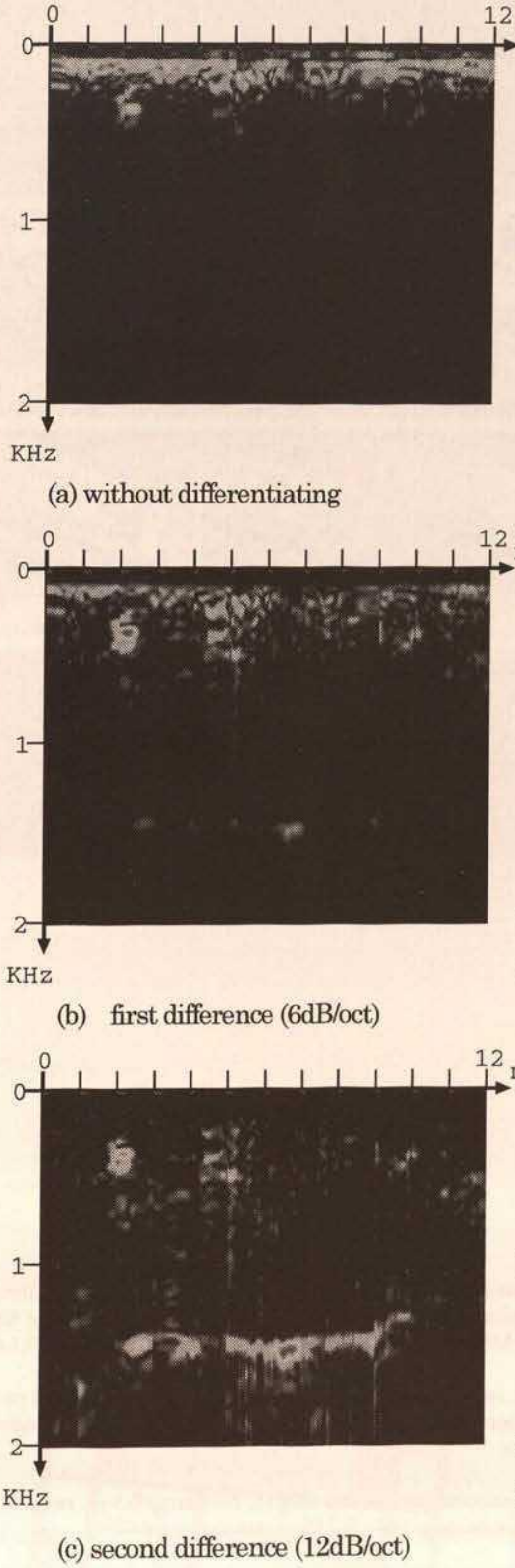
As a pre-processing, a technique of emphasizing higher frequencies is introduced. In a pulse GPR, a time-varying gain (STC) is applied in order to compensate for propagation loss, but this technique is not applicable to a continuous-wave GPR. In the FM-CW GPR, a signal from a deeper target appears in higher frequency domain. It is well known that differentiating a time-varying signal results in emphasizing the higher frequency part of its power spectrum at the slope of 6dB/oct. By differentiating a beat signal of the FM-CW GPR, deeply buried targets appears more clearly in the GPR image.

Many spectral-estimation methods such as FFT, MEM (Maximum Entropy Method), filter bank, *etc.*, are applicable for detecting the beat frequencies. They have both advantages and limitations, respectively; so, a proper method should be chosen for the purpose, multiple methods may be also available.

In this FM-CW GPR, the transmitter frequency changes from 100 MHz to 500 MHz in a half period of the modulating triangular waveform. By setting the length of the time window for spectrum analysis shorter than a half of the modulation period, we can select the frequency band used for imaging; the higher frequency, the shorter wavelength, then the higher resolving power, physically.

A delay time T is detected as a peak at a frequency of f_b ($= aT$) in the power (amplitude) spectrum of the beat signal in the FM-CW radar; furthermore, the delay time T also appears in the phase term of the spectrum. So, we can make another image using phase spectra. In a phase spectrum by FFT, a step-like change of phase appears at a frequency corresponding to the delay time T. Since there are some cases where detection of step-like change is easier and/or more accurate than peak detection, a FFT phase spectrum image of the FM-CW GPR is available.

Kamei, H. et al. (1996), "A 100–500 MHz Band FM-CW Ground Penetrating Radar for Archaeological Prospecting", Abstracts of Archaeometry 96, *Urbana,* USA, May 20–24, p. 57



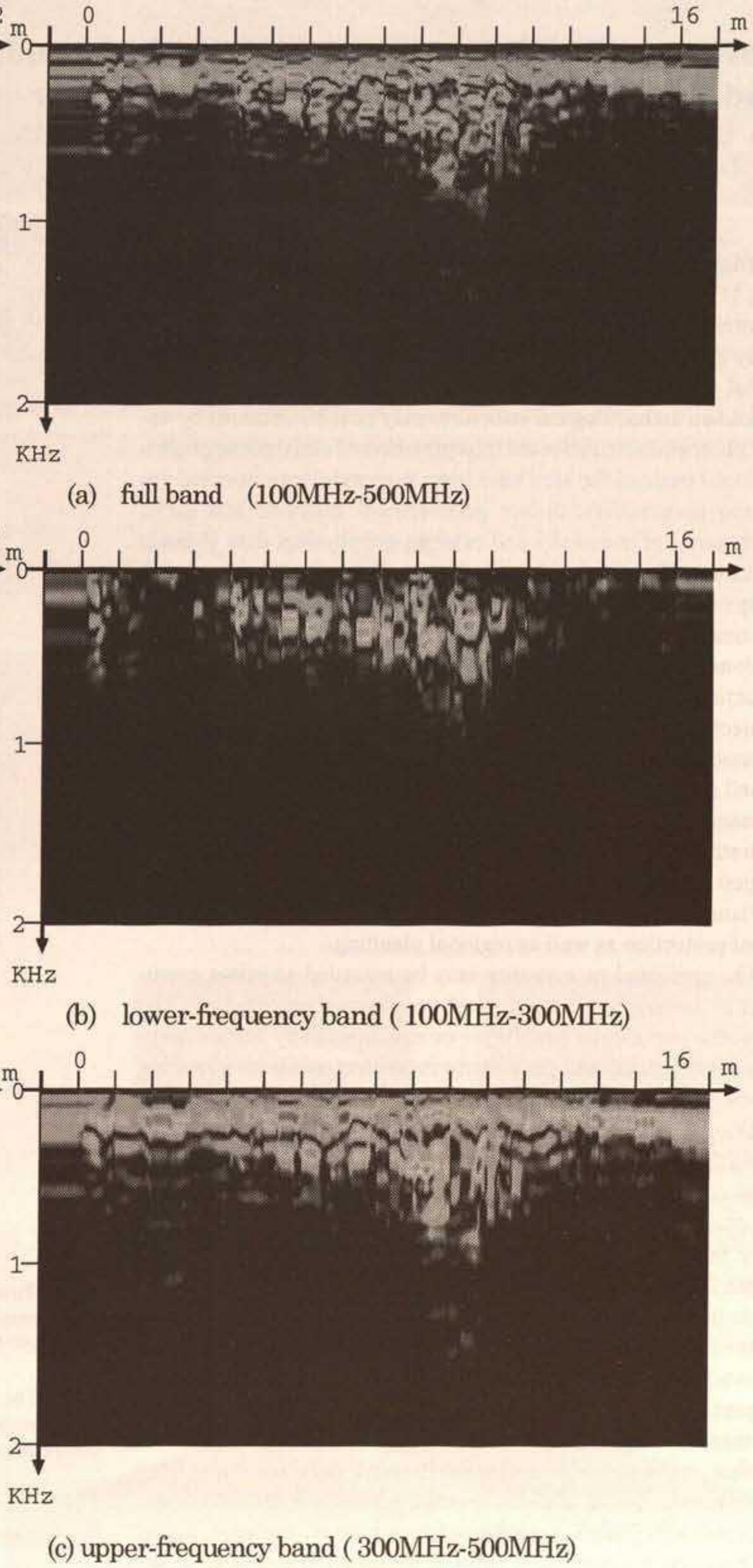


Fig. 1. Emphasizing higher frequency by differentiating a beat signal of the FM-CW GPR (Sakurai mounded tomb, Fukushima pref., Japan, AD 4C).

(a) without differentiating
(b) first diffenrence (6dB/oct)
(c) second difference (12dB/oct)

Fig. 2. Effect of frequency band on profiles of the FM-CW GPR (the brick floor of Shimotsuke brick kiln built in 1889, one of the oldest brick kilns in Japan, Gunnma pref.)

(a) full band (100 MHz-500 MHz)
(b) lower-frequency band (100 MHz-300 MHz)
(c) upper-frequency band (300 MHz-500 MHz