Detection of Objects Buried in Wet Snowpack by an FM-CW Radar

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Abstract—**A real aperture FM-CW radar system was developed for the detection of objects buried in heavily wet snowpack. This radar uses the *L* band microwave frequency with a maximum output power of 100 mW, and utilizes digital signal processing techniques. A laboratory simulation and two field experiments were carried out to detect and map various objects embedded in the snowpack. It was possible to map a metallic pipe 3 cm in diameter at a depth of 70 cm and a 10 × 60 cm metallic plate at a depth of 90 cm in the natural wet snowpack. Fundamental detection results are demonstrated in this paper.**

I. INTRODUCTION

THERE is an urgent need to detect objects buried in snow in regions with heavy snowfall. Examples of buried objects are avalanche victims, hydrants, metallic road guards, and metallic garbage or objects which may obstruct snow-shoveling machines, etc. There are numerous object examples and associated problems concerned with snow. These needs are enhanced by increasing human activities in snowy regions.

Microwave radar seems to be the most likely answer to these detection problems. Microwave radars for subsurface detection can roughly be classified into two types: One is a widely used pulse radar, and the other is a continuous wave radar. The most significant feature in the application of snow subsurface detection is a short-range measurement in a relatively shallow region. The target is located at most within a few meters. This short-range measurement demands a pulse radar to be quite sensitive in time resolution. In order to obtain high resolution in range, the pulse radar must produce extremely short pulses and the receiver must have the ability of discriminating time differences of the order of pico seconds. Everything concerned with range resolution is dependent on the time domain resolution. This requirement leads the pulse radar to be quite expensive, not suitable for commercial use. On the other hand, continuous wave radar measures the range in the frequency domain. The range resolution is dependent on the resolution in the frequency domain which can be adjusted arbitrarily and easily compared to the pulse radar. Therefore the frequency modulated continuous wave (FM-CW) subsurface radar [1], [2] and holographic radar [3] that detect buried objects in snowpack are promising. The imaging performance of the holographic radar may be superior to that of the FM-CW radar; however, the holographic radar needs much expensive equipment and operation time in actual radar operations. Our ultimate goal is to realize a low-cost, low-power, easy-to-handle, compact and real time subsurface radar system. In this regard we have been engaged in developing a practical FM-CW radar system which is capable of finding objects embedded in heavily wet snowpack in real time operation.

The radar is expected to be used in very adverse snow conditions; i.e., in a very highly dense and wet snow environment. Although natural snowpack, in general, consists of many horizontal snow layers whose electric properties are different, the snowpack may have undergone melting and refreezing repeatedly. Through the melting cycle, water flow destructs horizontal boundaries. Thus the snow boundaries of each layer become vague, and the snowpack becomes a mass volume filled with lossy inhomogeneties on the irregular ground.

Dielectric properties of wet snow have been reported at microwave frequencies [4], [5]. Even in the homogeneous snowpack which consists of wet and highly dense snow, a significant attenuation in electromagnetic wave propagation reduces sounding capabilities at frequencies above 3 GHz [6]. For example, for snow wetness of 3% and density of 0.4 (g/cm^3), the theoretical attenuation constant becomes 17.4 dB/m for 3 GHz, and 100 dB/m for 10 GHz [7]. The attenuation constant is almost in proportion to frequency. Furthermore, the attenuation is sensitive to water inclusion (wetness) in snow. If the wetness doubles in its percentage, the attenuation increases more than twice in dB [7]. In addition to these facts, snow properties change with time; i.e., the complex dielectric constant varies with time. The dielectric property of snow changes with temperature and the pressure of its own weight, experiencing refreezing and melting repeatedly.

Hence it is necessary to use a frequency as low as possible for deep sounding. In the lower frequency range, however, it is difficult to obtain high radar resolution and to make the antenna compact, because a relatively wide-sweep frequency is necessary for high-resolution FM-CW radar. From these considerations we have chosen a frequency range from 1.2 to 2.2 GHz for our system in order to accommodate the radar to practical use in our wet snow environment. Typical snow wetness on the Japan Sea side ranges from 1 to 14% [2], [7].

This paper presents results of detecting buried objects by an FM-CW radar. Emphasis is placed on detecting objects in natural stratified snowpacks. In Section II, the principle of the FM-CW radar is briefly described, and in Section III, the scanning and signal processing techniques for mapping the buried object in horizontal snow layers is outlined. Section IV shows the field experiment results of detecting several objects within a rather wet snowpack and a heavily wet dense snowpack.

Manuscript received April 18, 1990; revised November 1, 1990. This work was partially supported by a Grant-in-Aid for Scientific Research, Ministry of Education, Japan, and by the Sasamura Foundation.

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IEEE Log Number 9041929.

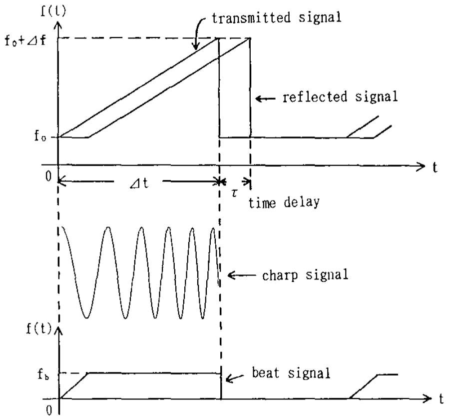


Fig. 1. Frequency versus time waveform of FM-CW radar.

II. FM-CW Radar Principle

The basic principle of FM-CW radar is shown in Fig. 1. The transmitted signal varies linearly with time. The signal reflected from a single target at a fixed distance arrives at the receiving antenna with a time delay of $2R\sqrt{\epsilon_r}/c$. The transmitted and reflected signals are mixed via a mixer, producing a so-called beat signal. This time-domain beat signal is transformed by an FFT operation into the frequency domain, resulting in the beat frequency f_b, which is proportional to the distance R:

$$R = \frac{c}{2\sqrt{\epsilon_r}} \frac{\Delta t}{\Delta f} f_b \tag{1}$$

where R = distance; $c = 3 \times 10^8$ m/s; f_b = beat frequency; Δt = sweep time; Δf = sweep frequency; and ϵ_r = relative permittivity of intervening medium.

It is possible to determine R if the relative permittivity of the intervening medium (snow) and beat frequency are known. The range resolution based on the FM-CW system is given by

$$\Delta R = \frac{c}{2\sqrt{\epsilon_r}} \frac{\Delta t\, f_c}{\Delta f\, N} \tag{2}$$

where $f_c = \frac{1}{2} \times$ (sampling frequency for beat signal); and N = number of sampling points in FFT.

Theoretically, one can change the range resolution by adjusting Δt and Δf according to (2), provided that the operating antenna has the same response over a wide frequency band and that the spectrum resolution in the frequency domain is narrow enough. However, in practice, the specification of a radar system is determined by many factors, such as the FFT execution time for real time operation, the frequency characteristics of the antenna in use, the snow response of microwave signals, etc. Since system design and resolution are dependent on the application, we assumed the following: (i) Maximum detection range in wet snowpack = 3 m; and (ii) range resolution = 6.1 cm in the air. Based on various microwave transmission experiments [7], we have chosen the FM-CW radar system specification as listed in Table I.

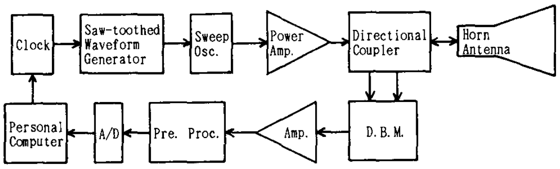


Fig. 2. Block diagram of the FM-CW radar.

TABLE I
Specification of the FM-CW Radar

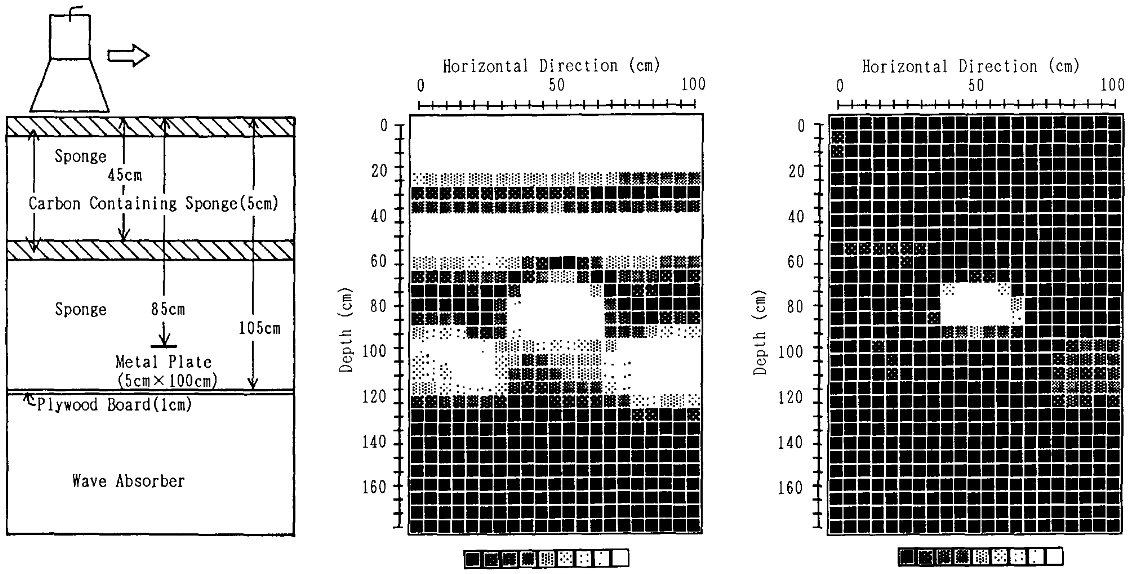
Frequency	1.2-2.2 GHz
Maximum power of generator	100 mW
Sweep time	5.2 ms
Range resolution	6.1 cm in the air
Sensitivity at mixer input	−42 dBm
Controller	16-b personal computer
Number of sampling points in the frequency domain	128

Fig. 2 shows the block diagram of the FM-CW radar system for object detection. A system clock triggers a sawtooth wave generator, which drives a sweep oscillator (HP 8620C). The oscillator generates, successively, a frequency-modulated continuous wave (1.2-2.2 GHz) at 5.2-ms period intervals. The microwave signal is divided into two parts by a directional coupler: One is used as a reference signal at a double balanced mixer, and the other is transmitted through a rectangular horn antenna. A backscattered wave from the target is mixed with the reference signal at the mixer, producing the beat frequency. Then the beat signal is amplified and reshaped in the preprocessing analog circuit, and finally is converted to digital signals in the personal computer system where the required signal processing such as FFT operations, graphic display, and system controls is executed.

III. Antenna Scanning and Signal Processing

FM-CW radar, in general, is used to measure a distance between the radar and a target by utilizing the frequency spectrum of the beat signal. The distance is determined by the peak position of the beat spectrum. All we obtain is one-dimensional information (distance). However, the spectrum has a two-dimensional shape (magnitude and frequency) characteristic to the target echo. If one utilizes a successive shape of the beat spectra resulting from an antenna-scan measurement, one can map an object in a two-dimensional space measured by both range direction (corresponding to distance) and azimuth direction (corresponding to the direction of antenna scan). This mapping is possible as long as the reflected microwave signal from the target produces the beat signal at a mixer, no matter how the intervening medium is. Thus it seems possible to map an object buried in snowpack.

Fig. 3(a) shows the scanning measurement arrangement and a model of buried objectes in lossy snowpack in a laboratory experiment. The object used in this experiment is a 5 × 100 cm metallic plate. The thickness is 1 mm. The plate was buried at a depth of 85 cm from the surface. The intervening medium consists mainly of sponge layers; partially of lossy sponge layers of 5-cm thick combined with carbon; and a 1-cm thick wood



(a) (b) (c)

Fig. 3. Laboratory simulation for detection of buried objects. (a) Snowpack model and measurement scheme. (b) Raw data obtained by the radar. (c) Processed data. Nine uniformly sliced quasi-gray scale levels have been used to cover the range from 0 to 2000 in the frequency domain.

TABLE II
DIELECTRIC PARAMETERS OF ARTIFICIAL SNOW AT 9 GHz

	Permittivity	Conductivity (S/m)
Sponge	1.06	0.001
Carbon combined sponge	1.4	0.18
Wood plate	1.3	0.01

plate as shown in Fig. 3. This stratified medium is modeled as a natural layered snowpack. The complex dielectric constants of the intervening materials measured at the frequency of 9 GHz by a standing value method using a rectangular waveguide are listed in Table II. These values contain errors of the order of 5–10%; however, the sponge corresponds to new fallen dry snow, the carbon combined sponge to wet lossy snow, and the wood plate to ice plate categories. These are considered to be typical values of the snow and ice medium [4], [5].

The antenna was scanned over the surface as indicated in Fig. 3(a). The scanning interval was chosen to be 5 cm. The magnitude of the spectrum for each scan is illustrated in Fig. 3(b), where the level is represented by a quasi-gray scale, with white indicating strong reflection. Nine uniformly spaced gray-scale levels have been used to cover the magnitude in the range from 0 to 2000 in the Fourier transformed domain. The horizontal axis corresponds to the scanned length (1 m), while the vertical axis corresponds to the depth. It is seen that there are many reflections due to dielectric discontinuities (impedance mismatch). The strongest reflection is caused by the interface between the antenna and the surface. The second strongest reflection comes from the second carbon combined sponge layer. Although the target is embedded well below these layers, one can identify the reflections due to this target.

Due to clutter, it is not easy to recognize the target by looking in Fig. 3(b). The usual snowpack consists of horizontal snow layers, which, in turn, makes us carry out some processing to retrieve target information from this characteristic structure. We make use of an averaging and subtracting method. First, we take the average magnitude of the spectrum in each column in Fig. 3(b), then we subtract it from the magnitude at each column. This simple operation renders the target clear by suppressing clutter (layer reflections), as shown in Fig. 3(c). This signal processing operation is executed quite rapidly in the personal computer (8086 + 8087 processor, 8-MHz clock), and does not affect the real-time operation. The total time needed for one radar display routine was about 1 s.

IV. FIELD EXPERIMENTS

In this section we present experimental results in actual snowpacks. As mentioned in the introduction, the microwave attenuation determines the maximum range in snowpack. The range performance of the radar is dependent on the dielectric property of the snow under experiment. Thus in order to check the system's performance, we carried out two field experiments: One was aimed at checking maximum range in snowpack, and the other, at detection.

A. Range Detection

The first experiment was carried out February 9, 1988 at Yunotani Village, Niigata Prefecture, Japan. The snowpack under the experiment is illustrated in Fig. 4(a), where the physical

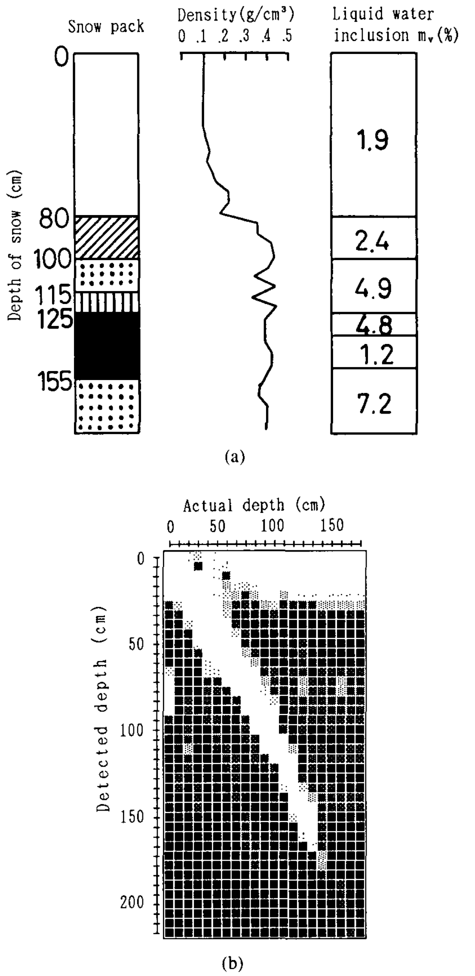


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Fig. 4. Range detection in a relatively wet snowpack. (a) Structure, snow density, and water inclusion of the snowpack. (b) Range detection result of a 5 × 100 cm metal plate.

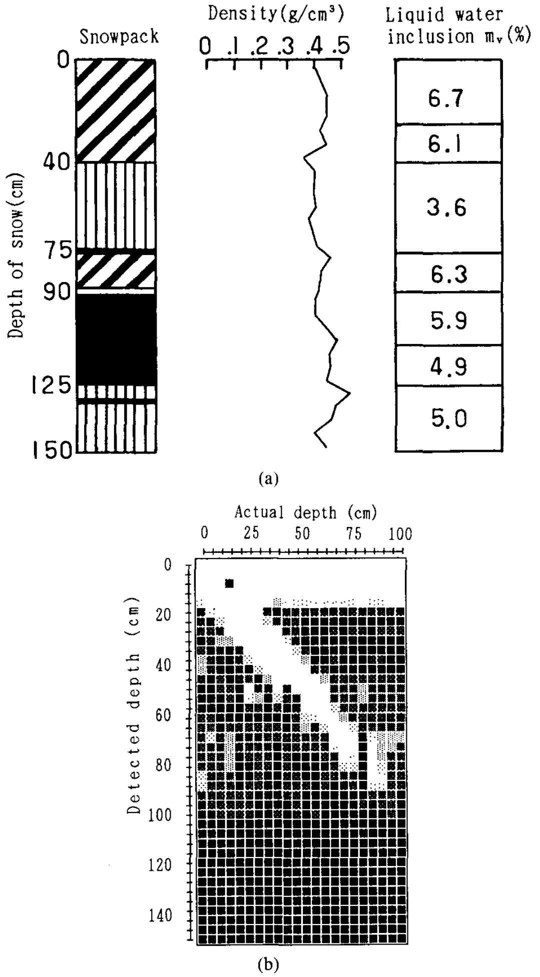

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Fig. 5. Range detection in a heavily wet snowpack. (a) Structure, snow density, and water inclusion of the snowpack. (b) Range detection result of a 5 × 100 cm metal plate.

parameters of the snow layers are shown. The depth was more than 2 m, which is a typical snow depth in this region.

We first examined the maximum depth at which this radar could detect the target (the same metal plate which was used in the laboratory experiment). We dug the snowpack down to the ground, making the cross section of the snow layer apparent. Then the target was inserted horizontally into the snowpack, being careful not to disturb the snow structure, starting from the bottom. The range detection result is shown in Fig. 4(b), where the horizontal axis represents the actual target depth from the surface, and the vertical axis is the depth measured by the radar. Once the target depth by the radar in snowpack is obtained, then it is possible to determine the average permittivity of the snowpack and to calibrate the range according to (1). The maximum detection range in this case was approximately 150 cm. The condition for determining the maximum range is such that we divide the whole magnitude range of the spectrum into nine equally spaced levels from the outset (see Section II). If the measured magnitude of the target at a position becomes less than the smallest threshold level, then the distance between the antenna and target is specified as the maximum range. Since the magnitude of the measured spectrum varies with the target size and shape as well as the snow property, we used the radar system and the same target (metal plate of 5 × 10 cm) throughout the work.

Fig. 5 shows another result of range detection. This experiment was carried out on March 15, 1988 at Yamakoshi Village, Niigata Prefecture, Japan. The snowpack was wet, hard, and heavy due to repeated freezing and melting cycles throughout the winter, coupled with rainfall on March. The structures of the snowpack is shown in Fig. 5(a). The maximum detection range was approximately 90 cm.

It should be noted that there is a place where no reflection occurs (see a row of 80 cm data in the horizontal axis in Fig. 5(b)), even though the target is within the detectable range. This seems to be caused by the standing wave phenomena in the

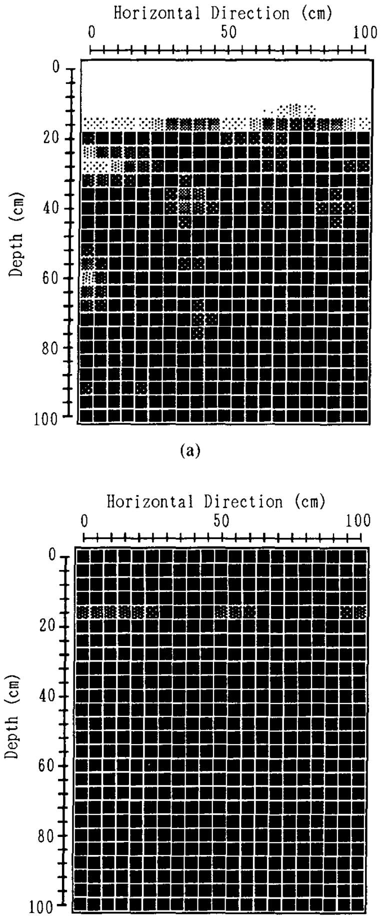

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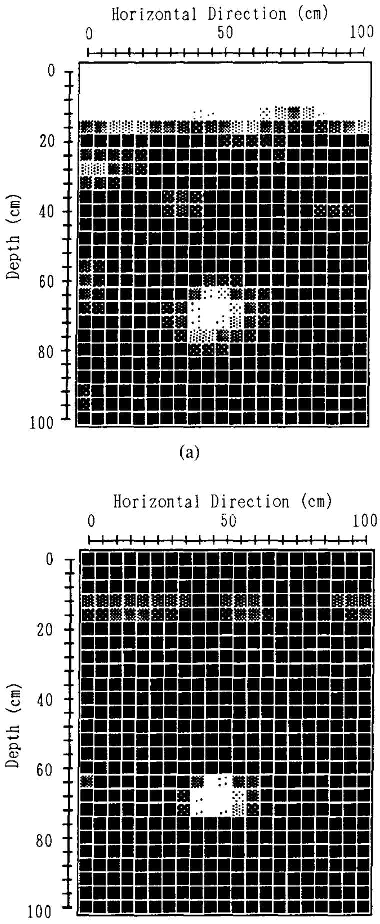
Fig. 6. Cross-sectional echo from the wet snowpack measured on March 1988. (a) Raw data. (b) Processed data.



(a)

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Fig. 7. Detection result of metallic plate "A" (5 × 100 cm) buried at a depth of 70 cm. (a) Raw data. (b) Processed data.

TABLE III
BURIED OBJECTS (UNIT IN CM)

	Width	Length	Thickness	Buried Depth
Metallic plate A	5	100	0.1	70
Metallic plate B	10	60	0.1	90
Copper pipe	3	100	0.3	70
Metallic can	8.5 cmϕ	20	0.02	60
Concrete block	19	39	10	60

snowpack. Since snowpack consists of many different horizontal snow layers, the structure viewed in the vertical direction can roughly be modeled as a cascaded transmission line consisting of many different layers, each having its own characteristic impedance. This transmission line model holds for the condition that the wave is sent into orthogonal to these layers underneath the antenna and that the field strength is measured in the far-field region where the wave is considered as a plane wave [11]. The far-field region in this experiment is a region of over about 30 cm from the antenna in the snowpack. If the object is placed where the electric field is small due to a standing wave phenomenon caused by impedance mismatch at adjacent layer interface, then it reflects very weak signal, which results in no detection.

From Figs. 4 and 5 it is clear that the maximum detection range is dependent on the dielectric property of the snowpack under the experiment. The dominant factors are the snow wetness of each layer, which governs the attenuation, and the layer structure, which relates to the standing wave phenomenon.

B. Object Detection

Buried-object detection measurement was carried out on the second experiment. Fig. 6 shows reflection from the snowpack where no objects are inserted. The strongest reflection came from the air–snow interface. However, the interior of the snowpack was relatively homogeneous. Then we buried several objects in the snowpack (listed in Table III). Using the antenna

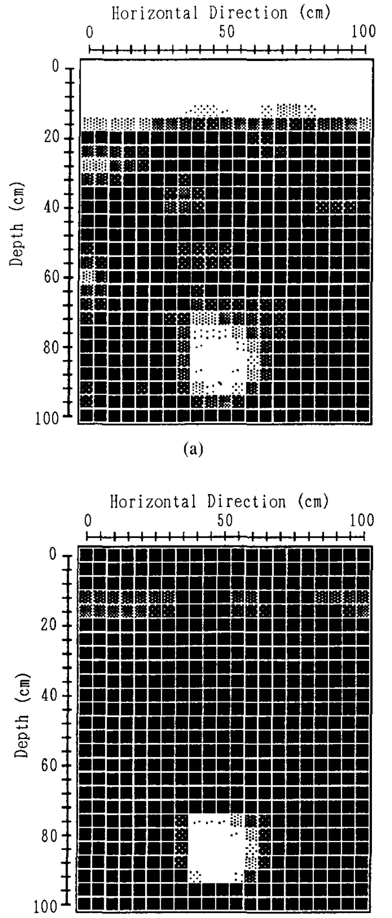

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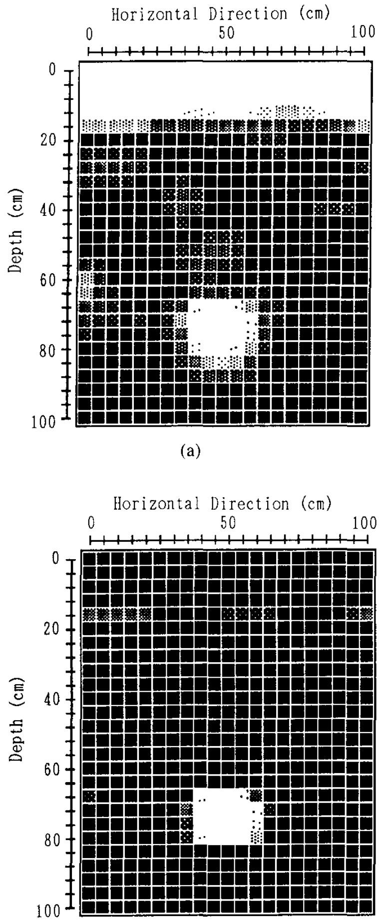
Fig. 8. Detection result of metallic plate "B" (10 × 60 cm) buried at a depth of 90 cm. (a) Raw data. (b) Processed data.



(a)

(b)

Fig. 9. Detection result of a copper pipe (3 × 100 cm) buried at a depth of 70 cm. (a) Raw data. (b) Processed data.

scanning method we could map these objects, as shown in Figs. 7-11. The detected object locations coincide with the actual locations, as expected. For the thick object (concrete block) shown in Fig. 11, multiple reflections due to the top and bottom surfaces of the object structure cause a broad object distribution in the range direction. In all cases, the scanning interval was chosen to be 5 cm; which was determined by the convenience of actual radar operation in the lossy snow environment.

In Figs. 7-11 the raw (unprocessed) data and processed data are illustrated in pairs. If the intervening medium consists of horizontal layers, this simple averaging and subtracting technique is effective for mapping buried objects.

V. CONCLUDING REMARKS

We have demonstrated the detection results of buried objects in natrual wet snowpack by using an FM-CW radar operating in the 1.2 to 2.2 GHz microwave frequency band. It was possible to map metallic objects larger than 5-cm wide, buried at least 80 cm from the snow surface, even if the snowpack was heavily wet (snow wetness more than 5%). In order to map buried objects distinctively, an averaging and subtracting technique was successively employed for horizontally layered snowpack.

This FM-CW radar is aimed at detecting objects within snowpack. The very first requirement is to find buried objects quickly; i.e., to check the existence of an object in the snow. The total time needed for each radar scanning and display routine was 1 s, which is allowable in real-time operation.

We have not employed the holographic or synthetic aperture technique for high-resolution imaging, because these techniques require much computation time, which does not serve our purpose. However, in order to map buried objects precisely this real aperture radar system needs a pencil beam antenna that has the same characteristics over a wide frequency range and an optimum sampling interval. The former will lead us to use antennas of impractical size, while the latter imposes a sampling optimization problem—if the interval is too small, the detected-object distribution is larger than the real object; if the

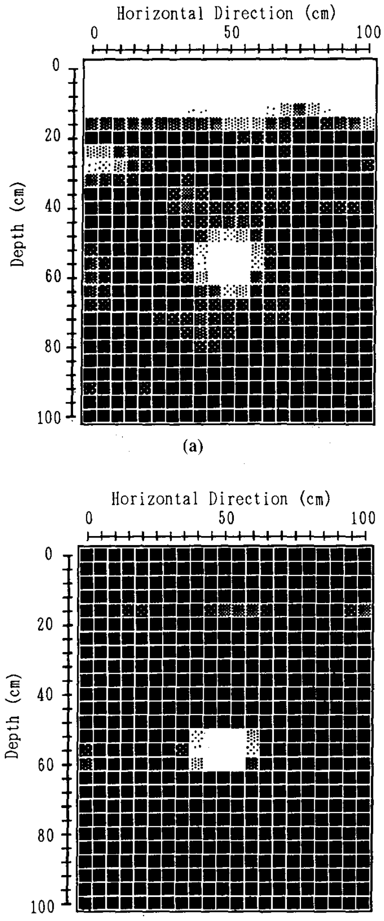


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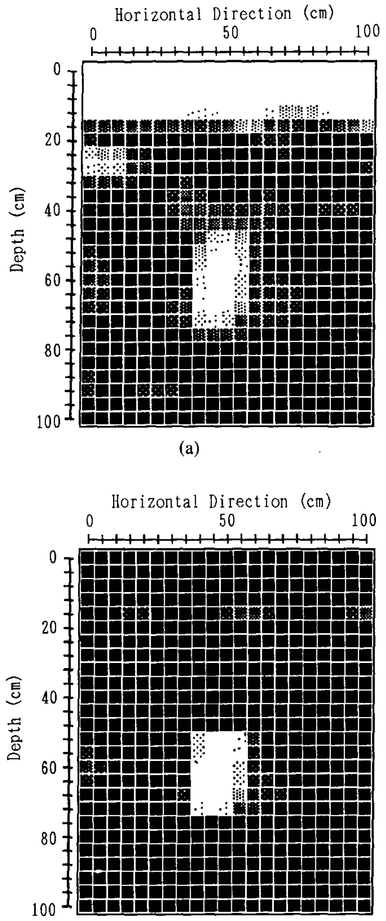
Fig. 10. Detection result of an aluminum can (8.5 × 20 cm) buried at a depth of 60 cm. (a) Raw data. (b) Processed data.



(a)

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Fig. 11. Detection result of concrete block (39 × 19 × 10 cm) buried at a depth of 60 cm. (a) Raw data. (b) Processed data.

interval is too large, the object may be missed or lost in relation to the antenna pattern in inhomogeneously stratified and lossy snowpack medium. It should be noted that the antenna pattern of this FM-CW radar in such a complicated medium cannot be specified due to a wide sweep frequency operation.

Hence there still remains a problem of how to develop an optimum antenna for the lossy snowpack environment and choose an optimum sampling interval. Our research here is phenomenological, insofar as we are now engaged in the following research and development:

1) Impedance matching at the air-snow surface over a wide frequency band.

2) Software development to improve the man-machine interface.

3) Use of special digital signal processing circuitry in computer implementation. Computation time needed for radar operation will be considerably reduced by it.

4) Increased image reconstruction of buried objects by the synthetic aperture technique coupled with 3).

ACKNOWLEDGMENT

The authors are grateful to M. Mitsumoto and T. Adachi for drawing the figures, and to G. Montenegro for reviewing the manuscript at Niigata University.

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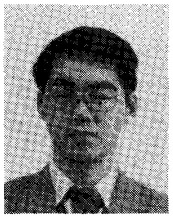

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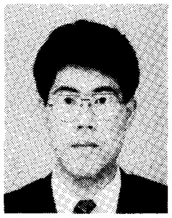

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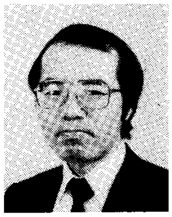

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