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STEP FREQUENCY RADAR FOR THE MEASUREMENT OF SEA ICE THICKNESS

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Abstract: The preliminary experiments have been carried out to test the fundamental functions of the step frequency radar. This radar aims at measuring the thickness of the Antarctic sea ice, which transmit 32 different frequencies in a stepwise fashion between 300 and 796 MHz. The radar has the following details; a) the maximum transmitting power: 400 mW, b) the range resolution: about 0.3 m in the air, c) the maximum observable distance without an ambiguity; about 9.1 m in the air, and d) the transmitting and receiving antennas: two cavity-backed spiral antennas whose sense of circular polarization is mutually opposite. The experiments in the anechoic chamber have proved that this radar system could have successfully detected the iron pipe buried in the dry sand and the aluminum plate placed under the sand box. This result suggests that with this radar system an airborne survey of the sea ice thickness will become possible.

1. Introduction

Recently, there has been a great increase in man's interest in the remote sensing of sea ice that covers roughly 13% of the surface of the world ocean. It is important for the radiation budget of the Earth (*e.g.* WEEKS, 1981), because presence of the sea ice causes a drastic change in the albedo of the sea surface (from 0.1 for open water to as high as 0.85 for ice). Monitoring of sea ice is also important for the navigation of the icebreakers of the Antarctic expedition teams. Satellite or airborne active and passive microwave remote sensors have provided useful information about surface conditions of sea ice (*e.g.* ZWALLY *et al.*, 1983; OKAMOTO *et al.*, 1983). However, the observation of the ice thickness by the airborne or the satelliteborne microwave remote sensors has not yet been realized, because sea ice includes a myriad of tiny liquid inclusions of brine, which is a high loss material for microwaves (CAMPBELL *et al.*, 1978).

We report in this paper the development of a step frequency radar at UHF band to measure sea ice thickness aiming at the practical airborne step frequency radar. Preliminary experiments to test the fundamental functions of the step frequency radar have been carried out in an anechoic chamber. The application of the present system to the measurement of sea ice thickness has been discussed, referring to the results of the preliminary experiments.

2. Step Frequency Radar

Some types of radars have been applied to measurements of thickness of lake ice or sea ice, such as the pulse radar (COOPER *et al.*, 1976), the impulse radar (CAMPBELL and ORANGE, 1974), the HISS (Holographic Ice Surveying System) radar (IIZUKA *et al.*, 1976) and the step frequency radar. The step frequency radar has been proposed by IIZUKA (1978), IIZUKA *et al.* (1984) and WU (1978). In the step frequency radar, the distance is measured by observing the change in the phase of the received signal with respect to a change in the frequency of the transmitted signals. For a given change $\Delta\beta$ in wave number (or in frequency), the change in the phase of the reflected signal from a target at a distance d becomes $2\Delta\beta d$ and hence is proportional to the distance d.

A block diagram of the developed step frequency radar system is shown in Fig. 1. The developed system uses two synthesizers for step frequency oscillators whose frequencies are very much stable. One oscillator is for the main signal to the transmitting antenna and for the reference signal and the other oscillator is for the local oscillator. The 32 transmitting frequencies change in a stepwise fashion at equal frequency steps of 16 MHz between 300 and 796 MHz. The 32 local frequencies also change in a stepwise fashion at equal frequency steps of 16 MHz between 310 and 806 MHz. The received signal and the reference signal are both individually converted by the local oscillator down to 10 MHz at each corresponding step. The phase difference is then measured at 10 MHz by the vector voltmeter. The amplitude of the received signal and the reference signal are measured simultaneously by the vector voltmeter.

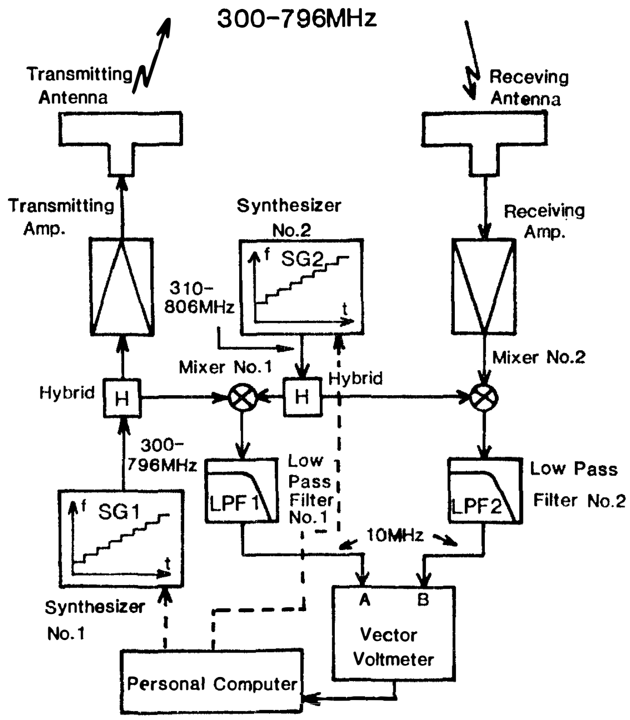


Fig. 1. Block diagram of the developed step frequency radar system with two step frequency oscillators.

The control to change transmitting and local frequencies in a stepwise fashion and data collection are performed by the personal computer. Two cavity-backed spiral antennas with mutually opposite sense of circular polarization are used as the transmitting and receiving antennas for the radar. There are two merits in choosing circular polarization in opposite sense. First, the antenna mutual coupling will be reduced, second the echo of the reflected signal with opposite sense of circular polarization is generally stronger than the echo of the same sense of circular polarization.

The characteristics of the step frequency radar are shown in Table 1. The maxi-

Table 1. Characteristics of the step frequency radar.

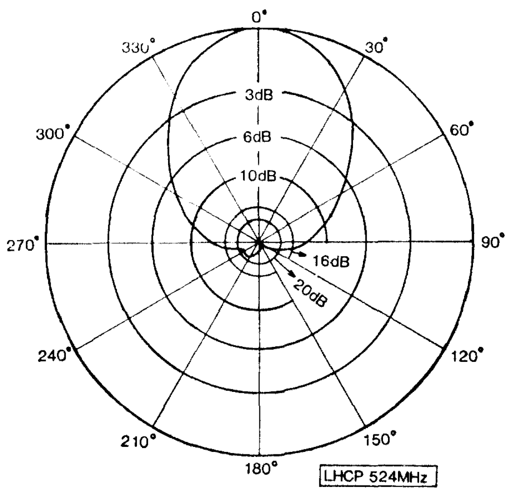
Transmitting frequency	300–796 MHz (32 frequencies with the step of 16 MHz)
Transmitting power	Maximum 400 mW (+26 dBm)
Range resolution	0.293 m in the air
Maximum observable distance without an ambiguity	9.08 m in the air
Antenna type	Cavity-backed spiral antenna (Right-handed circularly polarized and left-handed circularly polarized antenna)
Antenna gain	Details are shown in Table 2
Antenna beam width	Details are shown in Table 2
Isolation between antennas	More than 40 dB (when the distance between centers of antennas are 80 cm)
Antenna VSWR	Less than 1.5
Antenna diameter	About 45 cm
Antenna weight	About 5.3 kg
Time required for one measurement sequence	About 30 s

Table 2. Measured characteristics of left-handed circularly polarized cavity-backed spiral antenna.

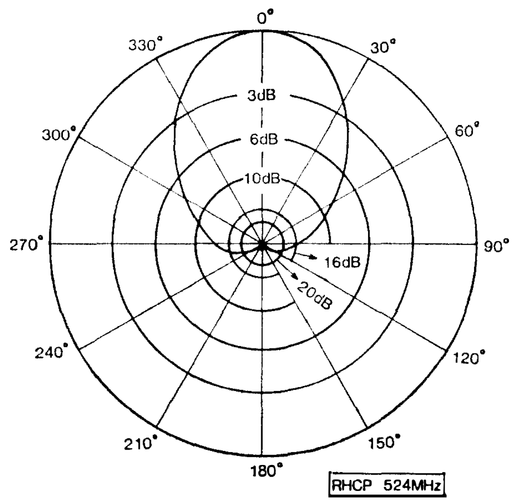
Frequency (MHz)	Beam width (3 dB)	Gain (dB)
300	81°	8.3
332	87°	8.4
364	82°	8.7
396	81°	8.5
428	72°	9.3
460	74°	9.1
492	72°	9.2
524	75°	9.1
556	68°	10.0
588	67°	9.6
620	64°	10.1
652	63°	10.0
684	63°	10.7
716	57°	10.3
748	56°	10.9
780	51°	11.6
796	54°	11.2

mum transmitting power is 400 mW. The range resolution is given by $\Delta y = c/(2N\Delta f)$, where c is the speed of light, N is the number of steps (32) and Δf is the frequency step (16 MHz). The value of Δy becomes about 0.293 m in the air. Maximum observable distance is given by $(N-1)\Delta y$ and becomes 9.08 m in the air. Detailed characteristics of the antenna gain and beam width (power is 3 dB down from the maximum value) are shown in Table 2.

Table 2 shows the measured characteristics of left-handed circularly polarized cavity-backed spiral antenna. The antenna characteristics of right-handed circularly polarized cavity-backed spiral antenna are almost the same as those of left-handed circularly polarized one. The antenna power patterns of left- and right-handed circularly polarized antenna at the frequency of 524 MHz are shown in Figs. 2a and 2b, respectively. These two antennas have good radiation characteristics for the wide band used in this radar.



(a) Left-handed circularly polarized antenna power pattern at 524 MHz.



(b) Right-handed circularly polarized antenna power pattern at 524 MHz.

Fig. 2. Examples of the power pattern of the cavity-backed spiral antennas.

3. Experiment

Two kinds of preliminary experiments were made in the anechoic chamber. One experiment was carried out to confirm the basic principle of the step frequency radar by measuring the distance between the antennas and the aluminum plate placed at some positions. Figure 3a shows the arrangement in this case, where the antennas look horizontally at the target. The distance between the centers of the antennas is adjusted to become 80 cm. The other experiment was carried out to detect an iron pipe buried in the dry sand and an aluminum plate placed under the sand box. Figure 3b shows the arrangement in this case, where the antennas look down vertically the surface of the dry sand. The distance between the centers of the antennas is adjusted to become 80 cm. The distance between the bottom surfaces of the antenna and the surface of the dry sand is adjusted to become 1 m. The wooden sand box is located on the wooden board. The distance between the surface of the dry sand and the bottom wooden board

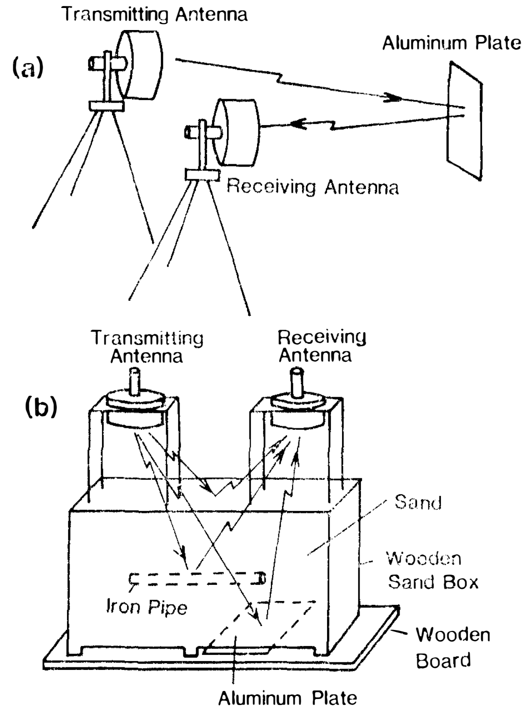


Fig. 3. Arrangements of the antennas and targets at the time of experiments. The distance between the centers of the antennas is adjusted to become 80 cm.
(a) Distance measurement experiment where antennas look horizontally at the target.
(b) Target detection experiment buried in the dry sand where antennas look down vertically the surface of the sand.

is about 70 cm. The VSWR of the antenna was measured in this arrangement and values were less than 1.5 for the whole range of frequencies. So, most of the power is radiated in the direction of the dry sand.

The measured data, *i.e.*, the differences of amplitudes (in dB) and phases (in deg.) between reference signal and received signal are dependent on the electrical length of the connecting cables, transmitting and receiving antennas and amplifiers, which vary with the operating frequency. This is compensated by storing a set of calibration data for each of the operating frequency. The calibration data were measured by placing a large aluminum plate at a distance of 1 m from antennas. The differences of amplitude (in dB) and phase (in deg.) between reference signal and received signal of a large aluminum plate at a distance of 1 m from antennas are stored for calibration data in the personal computer.

In the data analysis, the differences of amplitude (in dB) and phase (in deg.) between the measured data and the calibration data are calculated by the personal computer and thus normalized data are used for the Fast Fourier Transform. In this way, the amplitude and phase characteristics which are peculiar to the radar system can be compensated. The distance of 1 m from antennas can be considered the origin for distance measurement experiments. In the experiment inside the anechoic chamber, the 128 frequencies with equal frequency step of 4 MHz between 300 and 808 MHz were used for testing the stability of the synthesizers. The range resolution is 0.293 m in the air and this value is the same as that shown in Table 1, but the maximum observable distance without ambiguities become as large as 37.2 m in this case.

4. Results

Figures 4 and 5 show the results of distance measurement experiments. The arrangement of the antenna and the target at the time of the experiment is shown in Fig. 3a. A result of experiment when the aluminum plate is placed at a distance of 3 m from the antenna is shown in Figs. 4a–4c. Figures 4a and 4b show relations of phase (deg.) *versus* frequency (MHz) and amplitude (dB) *versus* frequency (MHz), respectively. Phase and amplitude are normalized by the calibration values measured for a large aluminum plate located at a distance of 1 m from the antennas. Figure 4c shows results of Fast Fourier Transform. The ordinate stands for intensity of spectral power (relative value) and the abscissa for spectral number which corresponds to the distance. Number 0 corresponds to the distance at the calibration plane (1 m from antenna). The distance y_n from the calibration plane to the target is proportional to the spectral number n and is obtained from the expression $y_n=0.293n$ (m) in the air. As the target aluminum plate is located at a distance of 3 m from the antennas, the peak can be

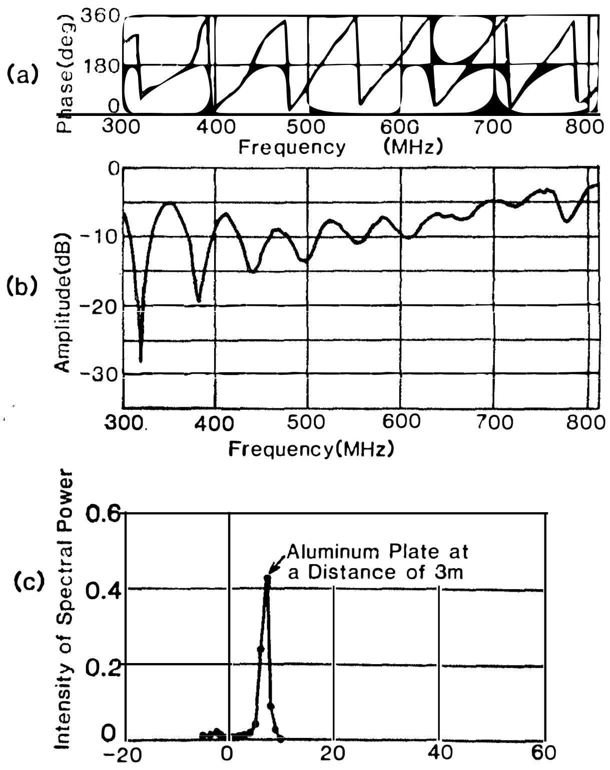


Fig. 4. Results of distance measurement experiment when the aluminum plate is placed at a distance of 3 m from the antennas.

(a) Phase versus frequency: Ordinate stands for phase (deg.) and abscissa for frequency (MHz).

(b) Amplitude versus frequency: Ordinate stands for amplitude (dB) and abscissa for frequency (MHz).

(c) Results of Fast Fourier Transform.

expected to appear at n=6.8. A sharp peak is observed actually at n=7, as expected.

Figures 5a–5c show the result of experiment when two aluminum plates are placed at distance of 2 and 2.6 m from the antennas, respectively. Figures 5a and 5b show relations of phase (deg.) *versus* frequency (MHz) and amplitude (dB) *versus* frequency (MHz), respectively. Figure 5c shows results of Fast Fourier Transform. The ordinate stands for intensity of spectral power (relative value) and the abscissa for spectral number which corresponds to the distance. As the distance y_n from the calibration plane to the target is given by the relation $y_n=0.293n$ (m) in the air, two peaks which correspond to two aluminum plates located at 2 and 2.6 m from the antennas can be expected to appear at n=3.4 and n=5.5, respectively. Two peaks are observed actually at n=3 and n=5. The result shows that it is possible to discriminate two targets which are 0.6 m apart in the air.

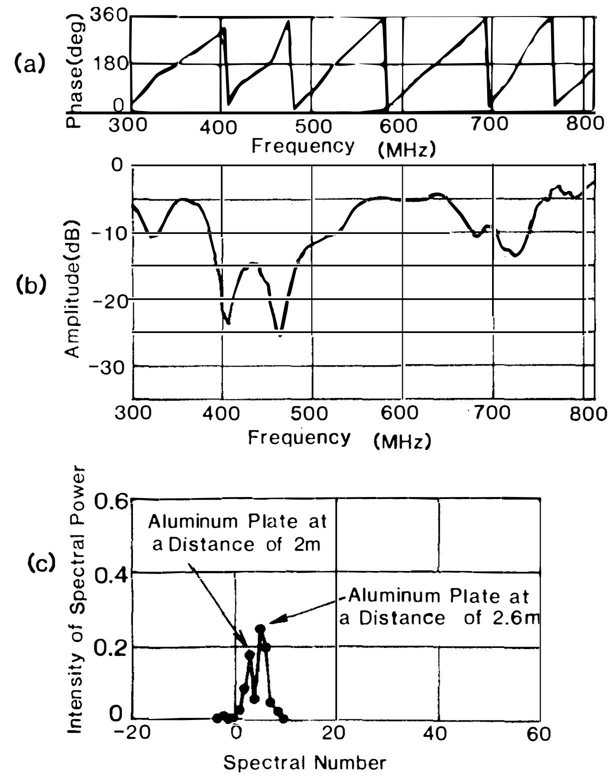


Fig. 5. Results of distance measurement experiment when two aluminum plates are placed at distances of 2 and 2.6 m from the antennas.

(a) Phase versus frequency: Ordinate stands for phase (deg.) and abscissa for frequency (MHz).

(b) Amplitude versus frequency: Ordinate stand for amplitude (dB) and abscissa for frequency (MHz).

(c) Results of Fast Fourier Transform.

Figures 6 and 7 show the results of Fast Fourier Transform in the case of target detection experiment. Arrangement of the antennas and targets at the time of this experiment is shown in Fig. 3b. Ordinates stand for intensities of spectral power (relative value) and abscissa for spectral numbers which corresponds to the distance.

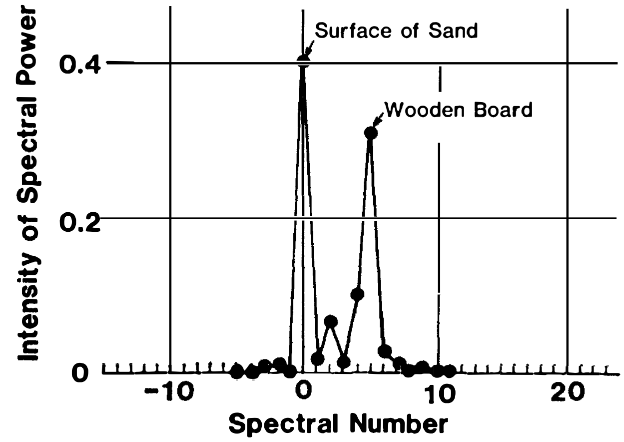


Fig. 6. Result of Fast Fourier Transform in the case of target detection experiment.

In the case of the experiment shown in Fig. 6, nothing is buried in the dry sand and only echoes of the surface of the sand and the bottom wooden board are clearly observed. The distance between the bottom surfaces of the antennas and the surface of the sand are adjusted to become 1 m. So, the peak at number 0 corresponds to the surface of the sand. The peak at number 5 corresponds to the bottom wooden board. The actual distance between the surface of the sand and the bottom wooden board, which is nearly equal to the depth of sand, is about 70 cm. The peak which appears at number 5 corresponds to the distance 1.46 ± 0.147 m if in the air. However, the real distance is 0.7 m. The refractive index η is given by the relation η=(thickness if in the air)/(real thickness) and becomes 2.1, if we assume the average value of the distance to be 1.46 m. The dielectric constant $\varepsilon = \eta^2$ becomes 4.4. So, the range resolution in the dry sand, $\Delta y = c/(2N\Delta f\sqrt{\varepsilon})$ becomes 0.14 m. So, the distance y_n from the calibration plane to the target at the spectral number n becomes $y_n = 0.14$ n (m) in this case.

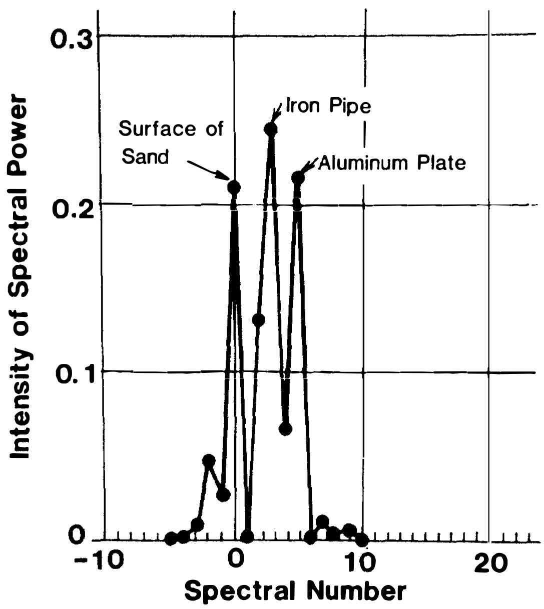


Fig. 7. Result of Fast Fourier Transform in the case of target detection experiment.

In the case of experiment shown in Fig. 7, an iron pipe is buried in the dry sand and an aluminum plate is placed just under the sand box. The iron pipe is buries about 40 cm below the surface of the sand. The distance between the surface of the sand and the aluminum plate is about 70 cm. The peak at number 0 corresponds to the surface of the sand which is at a distance of 1 m from the antennas. If the distance y_n from the calibration plane to the target is assumed to be given by the relation $y_n = 0.14$ n (m) in this dry sand, as was determined above, two peaks which correspond to an iron pipe and an aluminum plate can be expected to appear at n=2.9 and n=5, respectively. And these two peaks are observed actually at n=3 and n=5. This experiment aimed at identifying roughly the location of the target buried in the sand. However, it is worthwhile to point out that thicker material should be used in the experiment to determine precisely the refractive index η or the dielectric constance ε.

5. Discussion and Conclusion

The basic principle to measure distance by the step frequency radar was confirmed by the experiment in the anechoic chamber. The range resolution of 0.293 m in the air was verified by the experiment. The step frequency radar also showed its ability to detect buried target in the dry sand. This suggests its ability to penetrate into lossy medium such as sea ice and to measure the thickness of the lossy medium. In this radar, the good range resolution and the deep penetration are accomplished simultaneously by the low and wideband operating frequencies. This is not possible with a pulse radar. Applicability of a flexible coherent digital data processing technique is an excellent feature of the step frequency radar. This feature suggests that, with the step frequency radar, compensation for the dispersion effect within the wide band received frequency spectra can be accomplished, which is impossible with the impulse radar.

As the antenna beam of the step frequency radar is wide, it seems that various paths between transmitting and receiving antennas cause the ambiguity for the determination of peak of spectral power. However, as the area covered simultaneously with transmitting and receiving antenna beams is limited and the greater part of the backscattered power from the smooth surface target, which is used in the experiment, comes from the mirror symmetrical path among various paths, the peak of spectral power does not become so broad as that supposed. However, if the surface of the target is rough in comparison with the wave length, the peak of spectral power will become broad. Fine horizontal resolution can be achieved by a two-dimensional Wiener filter (IIZUKA *et al*., 1984). In order to attain this fine horizontal resolution, the transmitting and receiving antennas must be held together and scanned over the two dimensional area horizontally.

Attenuation coefficient data of the Arctic sea ice at UHF band measured by VANT (1976) were used to design the developed step frequency radar, because complex dielectric constant data or the attenuation coefficient data of the Antarctic sea ice at UHF band have not been published. If the attenuation coefficients of the actual Antarctic sea ice are unexpectedly large, they may become an obstacle in measuring the thickness of sea ice. In addition to this, the complex internal structure and the shape of the bottom surface of the actual Antarctic sea ice may cause the ambiguity of thickness measurement. However, we can conclude from the preliminary experiment in an anechoic chamber that the developed step frequency radar can measure the thickness of sea ice in principle.

The present system has been developed for the experimental use and is not compact. The practical system should be compact and easy to deal with. A lot of field experiments to measure the thickness of sea ice are going to be made around Syowa Station by the 27th Japanese Antarctic Research Expedition team using the developed step frequency radar. It is expected that useful data to develop the future airborne step frequency radar for the practical use will be gathered in the field experiments.

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