APPLICATION OF A NARROW BAND FM-CW SYSTEM IN THE MEASUREMENT OF ICE THICKNESS

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Abstract

An application of a narrow band radar technology for ice thickness measurement is presented. The method employed offers particular advantages for short distance measurements, conforms to FCC regulations for unlicensed operation and functions in unfavorable environmental conditions that affect optical and ultrasonic devices. The conventional FM-CW resolution is improved by inclusion of a phase shifter and by performing additional signal processing functions. Presented experimental data show better then 0.5" accuracy using only 150 MHz bandwidth.

Introduction

Microwave radar has been used extensively for long range measurements and to identify moving objects. These radar systems are generally large, built of expensive components and are unsuitable for measuring short distances. In general, the resolution with which range can be measured depends primarily on the absolute bandwidth available to make the measurement. A narrow band technique was developed that can significantly improve the resolution of radar systems. The narrow band operation permits the use of lower cost components and conforms to FCC regulations for unlicensed operation, which make the technology effective for commercial applications. The objective of the reported work has been the development of a contact ice thickness measuring instrument operating in the 5.725 to 5.875 GHz frequency band with a minimum ±0.5" accuracy over a measurement range of 2 to 24 inches.

Ultrasonic devices can provide short range measurement, but their accuracy is highly susceptible to temperature. Their limited range capability poses further restrictions on their use. Microwave radar, on the other hand, is relatively insensitive to the environment, has wide area coverage and can provide accurate range information.

In the conventional FM-CW radar, a frequency modulated signal generated by the system is reflected from the target and mixed with a portion of the reference transmitted signal. The distance is obtained from the frequency components contained in the resultant IF signal [1-3]. Numerous time-domain [4], and/or frequency-domain [3], signal processing methods have been utilized. Intrinsic to the FM-CW method is the periodic nature of the frequency modulation. Inherently, the IF frequency spectrum is discreet and therefore the measured range is limited to the theoretical resolution

$$\Delta r_o = \frac{c}{2\Delta f}, \tag{1}$$

where c is the propagation velocity of the RF energy and Δf is the effective modulation bandwidth. According to the above formula, to achieve the targeted 0.5" resolution in the ice ($\epsilon_r \approx 3$ at microwave frequencies) would require nearly 7 GHz effective bandwidth. Some improvement in resolution through additional signal processing in the frequency domain, has been obtained [3]. For a large target-to-clutter signal ratios, not a typical condition, a time-domain technique [4] also yields significant improvement.

Technical Approach

A block diagram of the narrow band FM-CW radar range measurement method is shown in Figure 1. It contains the elements of a conventional FM-CW radar, namely a radar system

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whose signal is obtained from a voltage controlled oscillator split between the transmit and local oscillator paths. A received signal, reflected from the target, is mixed with the reference signal. The newly incorporated element which leads to the stated accuracy improvement in the range measurement is the phase shifter . The frequency is swept in n_f discreet steps (stepped FM-CW operation) over an operating bandwidth Δf and at each frequency the phase is shifted in n_p phase steps. For each range measurement a total of $n_f n_p$ data points are acquired. For a target at distance R with an associated round trip propagation time $\tau=2R/c$ and an effective bandwidth Δf, the data sequence v_{IF} is shown to be

$$v_{IF}(i_p,i_f) = a\cos\left\{\Psi_1 - 2\pi(\Delta f\tau\frac{i_f}{n_f} + \frac{i_p}{n_p})\right\} \tag{2}$$

where the ranges of summation indexes i_p and i_f are $i_p=0,1..,n_p-1$ and $i_f=0,1..,n_f-1$ respectively, the amplitude a is a function of conversion and path losses and ψ_1 is a residual phase constant defined at $i_p=i_f=0$.

As will be shown below, this method will improve the measurement resolution by factor n_p and requires a phase shifter with a phase resolution of $2\pi/n_p$.

Given a frequency range Δf, at a fixed phase shifter state , e.g. $i_p=0$, the IF response, given by Eq.(2), due to a target at $R=\Delta r_o/n_p$ (i.e $\Delta f\tau=1/n_p$) will be a $2\pi/n_p$ sinusoidal segment. Successive segments are generated by frequency sweeps as the index i_p is incremented by 1 to produce a *single* 2π sinusoid. An $N=n_p n_f$ point complex FFT will have a single non-zero value at *the first* element. Similarly, a target at $R=k\Delta r_o/n_p$ (i.e $\Delta f\tau=k/n_p$) will generate a total of k 2π sinusoids, provided the phase shifter is incremented by $i_p k$ steps between frequency sweeps. A corresponding N point complex FFT has a single non-zero value at *the k'th* element.

In order to obtain the value of τ, it is necessary to examine the coefficients of the Fourier transforms of n_p data sequences $v_{IF}(i_p k,i_f)$ for $k=0,1...n_p-1$. The value of τ is related to the coefficient having a maximum value corresponding to the phase sequence which produces a full cycle of the IF waveform argument of the data sequence. The process has been reduced to the following transformation:

$$Z(k) = \sum_{i_p=0}^{n_p-1} e^{-j\frac{2\pi}{n_p}i_p k} \sum_{i_f=0}^{n_f-1} e^{-j\frac{2\pi\Delta f\tau}{n_p n_f}i_f k}\, \vec{v}_{IF}(i_p,i_f,k)\ , \tag{3}$$

where $\vec{v}_{IF}(i_p,i_f,k) = v_{IF}(i_p k,i_f) + j\,v_{IF}(i_p k+\frac{n_p}{4},i_f)$ and $k=0,1..,n_p n_f-1$. The ranges of summation indexes i_p and i_f are given above.

To examine the properties of the above transformation, substituting Eq.(2) into Eq.(3), yields

$$Z(k)=ae^{j\Psi_1}\sum_{i_f=0}^{n_f-1} e^{-j\frac{2\pi}{n_p n_f}(k-\Delta f\tau n_p)i_f}\ ,\ k=0,1...n_p n_f-1 \tag{4}$$

Of particular interest is a value of $k=k_o$ at which the magnitude of Z(k) is maximum, i.e $|Z(k_o)|=\max|Z(k)|$. By inspection of Eq.(4), this condition occurs when the exponent becomes zero. Since k by definition is an integer, the value $k_0=\Delta f\tau n_p$ must be also an integer.

Consider the case $n_p=1$, the conventional FM-CW (without the phaseshifter). The inherent limitation of this method is illustrated from the fact that $\Delta f\tau$ needs to be an integer in order to identify the target uniquely from the frequency spectrum $|Z(k)|$. Conversely, if $\Delta f\tau$ is not an integer value, the function $|Z(k)|$ has several non-zero coefficients. Figures 2a and 2b characterize the two cases respectively.

In the modified system with a phaseshifter, i.e $n_p>1$, $\Delta f\tau$ is no longer required to be an integer as seen in Figures 2c and 2d. It is evident that the result is quantized, as one expects when dealing with periodic signals in the time domain. The quantization interval of propagation time $\tau(k_0)$ defines the accuracy of this method, and is

$$\Delta\tau = \tau(k_0)-\tau(k_0-1) = \frac{1}{\Delta f\, n_p} \quad \text{or} \quad \Delta r = \frac{\Delta r_o}{n_p} \tag{5}$$

Referring to Eq.(1), we have shown that the modified FM-CW method yields an accuracy improvement by a factor n_p. The trade-off associated with the accuracy improvement is the need for additional signal acquisition and processing time. The number of data points has increased by a factor of n_p relative to a conventional FM-CW system with the same bandwidth Δf.

Experimental Work

The experimental system used in the evaluation of the ice thickness radar method was designed to meet the 0.5 inch accuracy within the 5.725 to 5.875 GHz band allocated by the FCC for unlicensed commercial applications. The experimental set-up consists of a microwave assembly controlled by a personal computer. Plexiglass has been chosen as a suitable medium, having a dielectric constant and loss tangent very close to that of fresh water ice. A typical plot of $|Z(k)|^2$ is shown in Figure 3. The index associated with the peak of the function is the measured quantity and is related to the ice thickness. A number of Δf, n_p and n_f combinations have been tested. The relevant results are presented in Figures 4 and 5 and summarized in Table 1. The actual thickness is referenced to the plane of the antenna aperture.

RF Bandwidth:	**350 MHz**	**150 MHz**
No. of phase steps:	32	64
No. of freq. steps:	8	4
Thickness range:	Measured error	
2" to 6":	±0.6"	±0.8"
6" to 10":	±0.3"	±0.4"
10" to 28":	±0.3"	±0.3"

Table 1 - Summary of Measurement Error in Simulated Ice

In order to maintain the desired accuracy, it was necessary to minimize the mismatch due to the antenna/plexiglass interface. Echoes caused by the mismatch gave rise to errors in shorter range readings. Experimental evidence indicates that the component of an echo or other close secondary target at the receiver must be at least 10 dB below the level of the main signal. Better discrimination was achieved at larger distances and increased bandwidth.

Discussion of Results

Referring to Table 1, the performance was evaluated on the basis of measurement accuracy at thicknesses greater than 4" with respect to the plane of the antennas, allowing for use of radome to facilitate antenna matching as well as mechanical requirements. Measured error in Figures 4 and 5 exhibits a mean and a peak component, the former can be removed by appropriate DSP corrections and the later is clearly within the desired ±0.5" accuracy for thickness greater than 4".

With additional bandwidth, accuracy as high as 0.07" has been demonstrated as well. With 150 MHz of bandwidth, improved antenna design and/or additional echo correction algorithms, less then 0.25" overall accuracy is feasible. The importance of the enhanced processing lies in the reduced dependence on a good antenna matching and consequently a lower product cost.

In addition to the ice thickness measurement, a wide range of other applications can be derived from the technology to serve industrial and commercial markets in level measurement, automotive collision avoidance and robotics.

Acknowledgement

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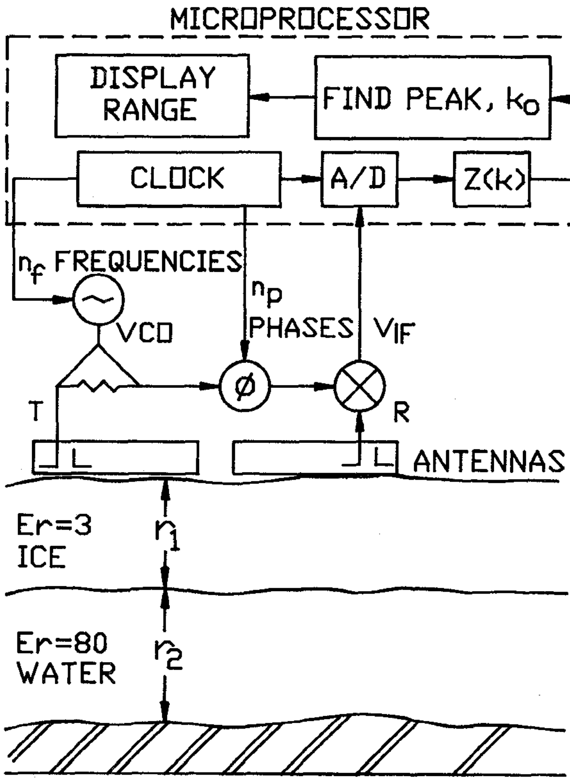
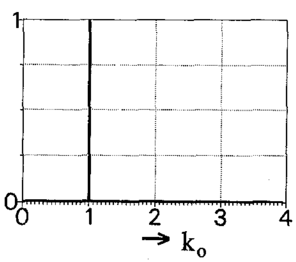
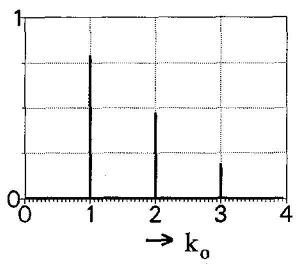


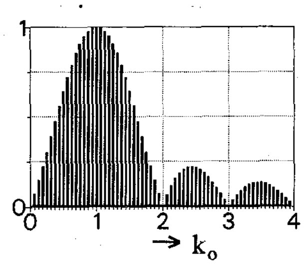
Figure 1: A Narrow Band FM-CW Ice Thickness Measurement System



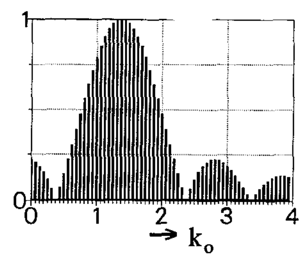
(a): Conv. Output for $\Delta f\tau$=**integer**



(b): Conv. Output for $\Delta f\tau$=**non-integer**



(c): Modified Output for $\Delta f\tau$=**integer**



(d): Modified Output for $\Delta f\tau$=**non-integer**

Figure 2: Comparison of Conventional (n_f=4) and Modified (n_p=16) FM-CW Outputs

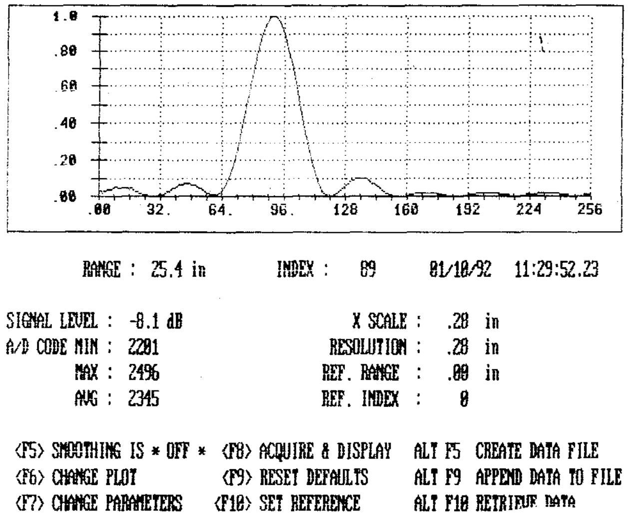


Figure 3: A Displayed Result of a Typical Thickness Measurement

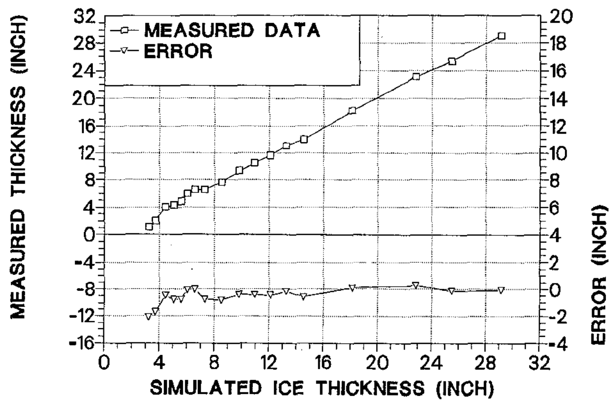


Figure 4: Results of Thickness Measurement Using 150 MHz Bandwidth

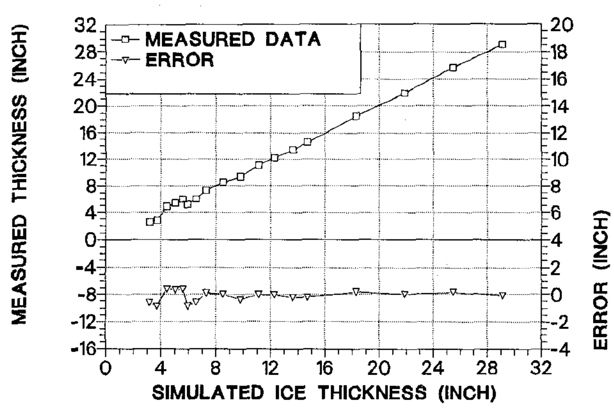


Figure 5: Results of Thickness Measurement Using 350 MHz Bandwidth