Calibration of a Wideband FMCW Radar used for Microwave SAR Imaging

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Abstact

A wide band FMCW Radar has been used for microwave synthetic aperture imaging of objects embeded in dielectric medium. Initial images formed the system where highly distorted due to numerous phase errors, the system has been calibrated through the use of a number of different calibrations. The two main types of errors are 1) the hardware system itself and 2) the phase terms in the received signal. The errors were eliminated by either changing the hardware system or developing a suitable algorithm in software to account for the error in the system. This system will be used for nondestructive evaluation and ocean wave scatterometery experiments.

Introduction

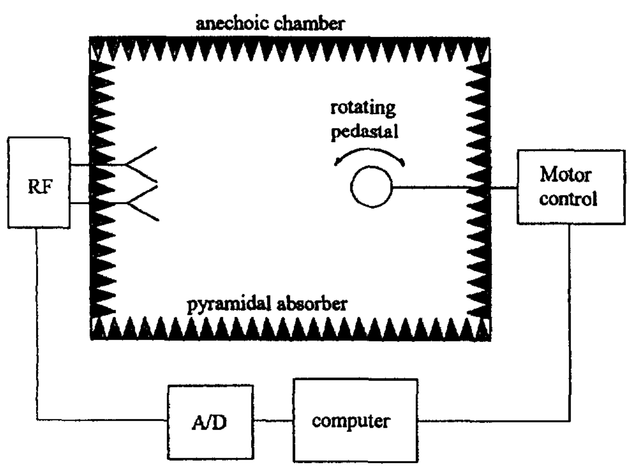
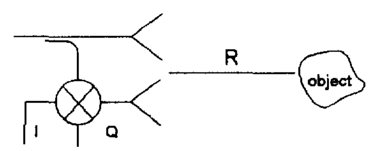


Figure 1. ISAR configuration

Over the past several months a frequency modulated continuous wave (FMCW) radar system has been developed for use in imaging objects embedded in a dielectric. The system is set up to form images in an inverse synthetic aperature radar (ISAR) configuration (FIG. 1) The radar stays stationary while the object is rotated through an angle θ. Data is collected from a number of angles to form an image.

System Overview



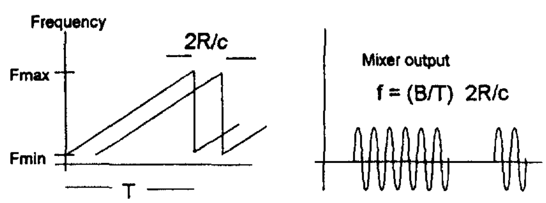


Figure 2. diagram of signals

The radar is an FMCW radar where the transmit signal (FIG. 2) is of constant amplitude and the frequency is swept linearly over the bandwidth. An expression for the transmit signal is:

$$\exp\left(j\left(\omega_o t + \omega_s t^2\right)\right) \quad |t| \le T/2$$

where ω_o is the carrier frequency and ω_s is the rate at which the frequency is swept. The signal is continuously transmitted, and the receive signal is a time delayed version of the transmit signal expressed as

$$\exp\left(j\left(\omega_o(t-\tau)+\omega_s(t-\tau)^2\right)\right)$$

Where the time delay is proportional to the range to the target. The receive signal is mixed with the transmit signal giving an IF signal and is given as:

$$\exp(j\omega_o\tau)\exp(-j\omega_s\tau^2)\exp(2\omega_s\tau t)$$

Where the frequency of the IF signal is proportional to the range to the target (FIG. 3).

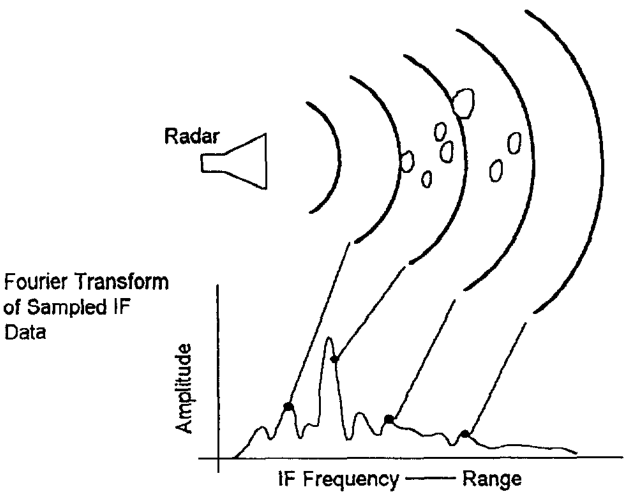


Figure 3. IF signal

Calibrations

The algorithm, used to form the image, requires that the distance to the center of rotation to be accurately known. To determine the distance to the center of rotation a flat object is placed at the center of rotation and a number of data sequences are taken. The data sequences are then fed through a fourier transform to determine the center of rotation. The bin of the maximum value is recorded and the distance is determined by using the range bin size for each of the fourier bins.

To increase the dynamic range of the system a correction for the antenna crosstalk is made. To perform this correction data sequences are taken with no targets in the anechoic chamber. Once a target is in the chamber the errors due to the antenna can be subtracted off. An example of the antenna correction is shown in figs 4-5. Figure 4 uses the antenna correction while figure 5 does not use the antenna correction.

Signal Processing algorithm

An electromagnetic wave traveling in free space can be modeled in two dimensions as:

$$h(x,y)=\frac{1}{\sqrt{j\lambda r}}\exp\left(\frac{j2\pi r}{\lambda}\right) \qquad r=\sqrt{x^2+y^2}$$

where r is the distance from a point target to the observation point, and λ us the operating wavelength. An image formation algorithm has been developed by H. Lee [1] that uses the above model and " back propagates " the received wavefield to a given distance. A two dimensional image can be formed by taking data at different angles and forming an image from a summation of those angles.

An example of an image is shown in (FIG. 6). The object is a small tricycle approximately 18 inches in length. The image was formed using 360 degrees at one angle increments.

To use the back propagation technique with an FMCW radar requires that the model be modified to account for the phase terms in the IF signal (FIG. 3), which are $j\omega_0\tau$ and $j\omega_S\tau^2$. The second term $j\omega_S\tau^2$ can be ignored since at microwave frequencies and short distances the term is on the order of 10^{-6}. The $j\omega_0\tau$ phase term in the IF signal is significant and on the order of radians per sample. To account for the $j\omega_0\tau$ phase term in the back propagation algorithm an extra term is added to account for the change in phase :

$$h(x,y)=\frac{1}{\sqrt{j\lambda r}}\exp\left(j\left(\frac{2\pi r}{\lambda_n}+\frac{4\pi r}{\lambda_o}\right)\right) \qquad r=\sqrt{x^2+y^2}$$

$$\omega_o\tau=2\pi f_o\cdot\frac{2r}{c}=\frac{4\pi f_o r}{c}=\frac{4\pi r}{\lambda_o}$$

$$\lambda_n=\frac{c\cdot Fsam}{2\cdot F_s\cdot n}$$

λ_n is the spatial frequency of the received wavefield at any given sequence in time. To determine the spatial frequency a fourier transform of the range response is taken. To determine the range response of the system a fourier transform of the recieved wavefield is taken and given by:

$$S[k]=\exp(j\omega_o\tau)\exp(j\omega_s\tau^2)\delta[k-2f_sT_{sam}N\tau]$$

$$where \quad \tau=2R/c$$

From the above the spacing between each of the range bin is given as:

$$\Delta r = \frac{cf_{sam}}{2f_s N}$$

If we now take a second fourier transform to get to the spatial frequency domain. The spacing between frequencies samples becomes

$$f_n = \frac{2f_s n}{cf_{sam}}$$

and the spatial wavelength $\lambda = 1/f$ is

$$\lambda_n = \frac{cf_{sam}}{2f_s n}$$

An example of the use of the phase correction is shown in figs. 7-8 at the end of the paper. Figure 7 is an image correcting for $j\omega_0\tau$ and figure 8 does not correct for $j\omega_0\tau$.

I and Q phase errors

The errors formed by in the inphase (I) and quadruture (Q) channels are from the mixer, and the Analog to Digital (A/D) Convertor. The mixer and A/D convertor errors can be modeled as the instantaneous difference of the I and Q components from 90 degrees. The main difference between the mixer error and the A/D convertor error is that the A/D converter error should be constant over an entire sampling period while the mixer error will vary with each sample. The variation in the mixer error is due to the fact that the mixer combines a signal at different frequencies each time. These errors where corrected for by an algorithm developed by R. Chiao[2]. An alternate approach that works well is to use a double balanced mixer with no quadrature output and digitize this signal and perform the hilbert transform.

References

1) Hua Lee and Richard Chiao, "Phase Error Estimation and Correction in Acoustic Microscopy," IEEE Transaction on Acoustics, Speech, and Signal Processing, vol. 38, no. 1, pp. 171-173, January 1990

2) Hua Kee,"Formulation of the Generalized Backward Projection Method for Acoustical Imaging," .ul IEEE Tranctions on Sonics and Ultrasonics, vol. SU-31, no.3, pp. 157-161, May 1984.

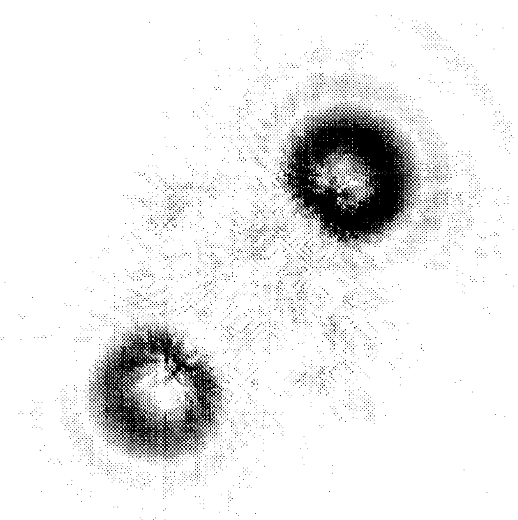


fig.4_antenna_correction

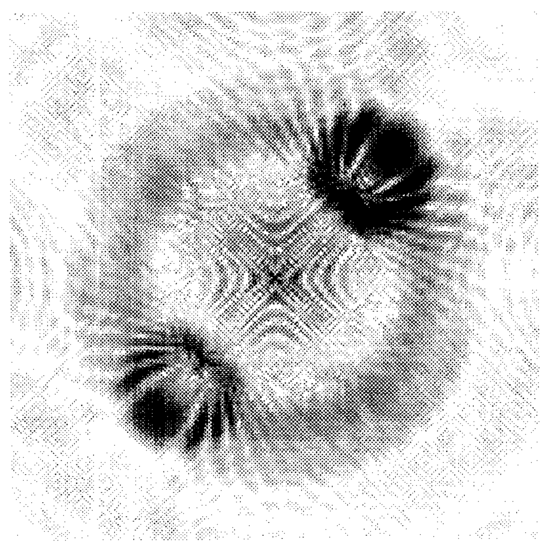


fig.5_no_antenna_correction

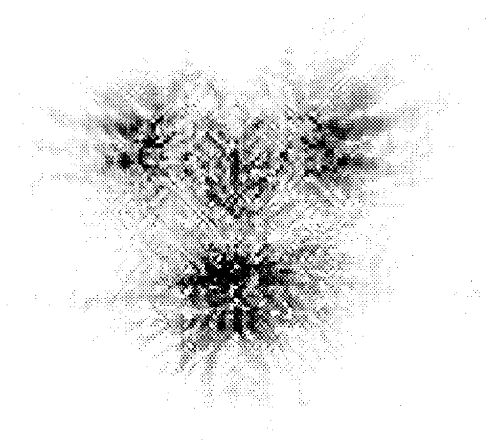


fig.6_tricycle

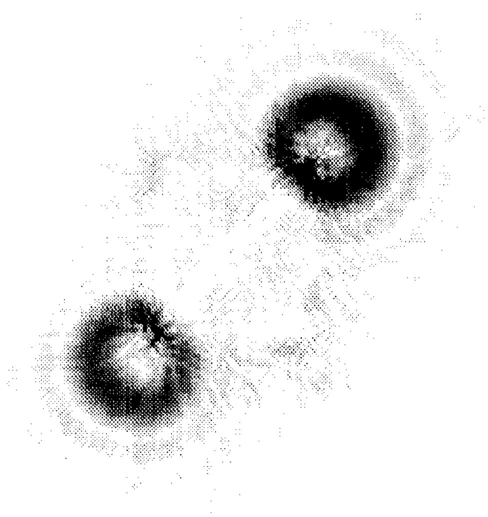


fig.7_phase_correction

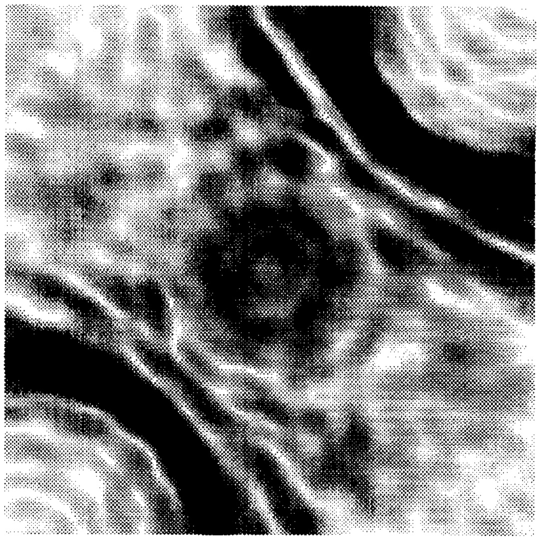


fig.8_no_phase_correction