3-Dimensional Object Reconstruction From Frequency Diverse RF Sensor Networks

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Abstract

Conventional phased arrays operate on narrow bandwidth principles to achieve resolution in imaging of buildings and other objects of interest. Unfortunately, such narrow bandwidth methods do not allow sufficient resolution to reconstruct objects of interest in 3 dimensions at low frequencies and with small apertures. We propose a method that is computationally efficient and allows dynamic use of spectrum to achieve high resolution 3 dimensional reconstruction of objects from small and distributed RF sensor networks. This method also allows available spectrum bands to be used on a non-interference basis.

I. Introduction

We will first develop the methodology for a composite chirp signal and show how this method produces a narrow high resolution pulse for multiple narrow bandwidth signals. We will then show how this composite pulse can be inserted into an array geometry either uniform or non-uniform to increase resolution on a target in 3 dimensions. Finally we will show different array configurations and how spatial array distribution can be traded for bandwidth.

II. Chirp Signal

The basis optimization algorithm begins by defining a linear FM or 'chirp' signal with sufficient bandwidth to provide the desired resolution on the target being observed. The chirp waveform with carrier frequency ω_0 can be described as

$$f_n(t) = \tilde{u}(t/T)e^{jbt^2}e^{jt\omega_0} \quad (1)$$

where $\tilde{u}(t)$ denotes a rectangular pulse of unit height and width, T, centered at the origin b is the chirp slope describing the rate over the frequency interval between $\omega_i \le \omega \le \omega_{i+n}$. Because the chirp is over the time interval $-T/2 \le t \le T/2$, the instantaneous frequency varies over a bandwidth given by

$$B_c = bT \quad (2)$$

To achieve wider bandwidth response we have multiple chirp increments of n = 1,.....,N where all chirp increments are combined in post processing. If we have an impulse response *I(t)* then our received signal for each chirp increment, is equal to

$$h_n(t) = f_n(t) \otimes I(t) \quad (3)$$

where $\otimes$ denotes the convolution operation. We also define the vector of outputs from the correlation over a finite window of time. If we now Fourier transform $h_n(t)$ you have $H_n(\omega)$. Combining each chirp increment we have

$$\tilde{H}(\omega) = \sum_{n=1}^{N} H_n(\omega) \quad (4)$$

We inverse fourier transform (4) to obtain $\tilde{r}(t)$ the impulse response of the combined chirp function. In the case of a target response we have

$$s_n(t) = f_n(t) \otimes T(t) \quad (5)$$

If we now Fourier transform $s_n(t)$ you have $S_n(\omega)$. The combined target response function from our object is then

$$\tilde{S}(\omega) = \sum_{n=1}^{N} S_n(\omega) \quad (6)$$

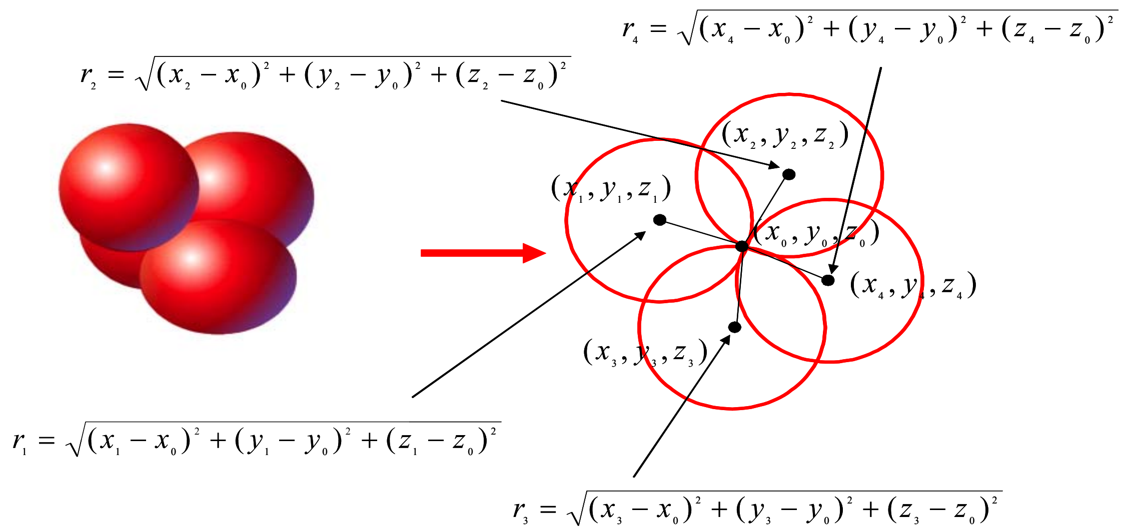

Figure 1 3 Dimensional distance estimation to any point in space requires 4 points.

The matched filter response of the target function in the fourier domain is then

$$\tilde{K}(\omega) = \tilde{S}(\omega)\tilde{R}(-\omega) \qquad (7)$$

Inverse Fourier transforming $k(t)$ is the combined target response. It is important to note that even though we have a high resolution pulse, this technique does not require high sampling rates due to the ability to sample the chirp pulses over slow time intervals thus reducing the real time computational burden on the algorithm.

II. Time Delay Array Structure

We now develop a measurement process for signal returns from an object radiated by a composite chirp signal. As is shown in Figure 1, to locate a signal return in three dimensions we need to measure the time delay between the signal at 4 points in space which is the unique intersection point between 4 spheres. The distance between the point and any one of the spheres is shown in equation 8.

$$r_n = \sqrt{(x_n - x_0)^2 + (y_n - y_0)^2 + (z_n - z_0)^2} \qquad (8)$$

The corresponding time delay to each point is given by.

$$t_n = \frac{r_n}{c} \qquad (9)$$

The angle to the target in 4 dimensions is given by the following two equations

$$\tilde{\theta}_x(n) = \sin^{-1}\frac{x_n}{r_n} \qquad (10)$$

$$\tilde{\theta}_y(n) = \cos^{-1}\frac{y_n}{r_n} \qquad (11)$$

If we now assume our signal is a single frequency measured from the radiation center of two dimensional rectangular isotropic phased array with spacing d at wavelength λ with radiation pattern as

$$G(\theta_x, \theta_y) = \frac{\sin[N\pi(d/\lambda)\sin\theta_y]^2}{N^2\sin[\pi(d/\lambda)\sin\theta_y]^2}\frac{\sin[M\pi(d/\lambda)\sin\theta_x]^2}{M^2\sin[\pi(d/\lambda)\sin\theta_x]^2} \qquad (12)$$

where N = the number of vertical columns of the array that give rise to the vertical angle θ_y and M = the number of horizontal rows that generate the angle θ_x. The above relationship assumes that the spacing between elements in the two directions is the same. Unfortunately such a pattern for element spacings that are not equal to $\frac{\lambda}{4}$ results in repeated grating lobes as is shown in Figure 2.

If we now introduce the composite chirp signal from the previous section as is shown in the following equation the combination of phased array signals as the intersect at the phased center of any element in 3 dimensions in space. The impulse response of this signal delayed by the amount that causes all of the return pulses to intersect at the time according to their distances from the reflector is.

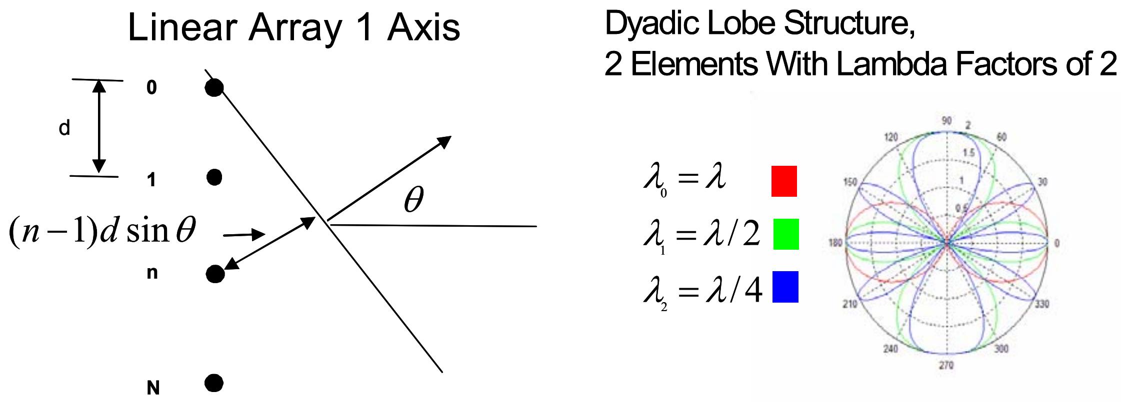

Figure 2 Grating lobe structure for uniform linear array

$$h(\tau) = h(\tau - t_1) + h(\tau - t_2) + \ldots h(\tau - t_N) \tag{13}$$

The corresponding correlated target response from a point reflector in space is:

$$k(\tau) = k(t_1 - \tau) + k(t_2 - \tau) + \ldots k(t_N - \tau) \tag{14}$$

The advantage of using the composite chirp pulse is that it allows multiple narrowband signals to be brought together to form a wideband pulse. Figure 3 shows the composite chirp implementation in terms of a phased array. We see this process in Figure 3 where each part of the composite chirp signal adds resolution to the measurement such that the entire signal provides a high resolution image. This allows the individual signals to be treated like narrowband signals as in the single frequency case. This enables much wider band signals to be created on phased arrays since the phase center at each frequency is not instantaneously distributed across the array as in the case of ultra-wideband signals. Thus such an ultra-wideband signal cannot localize an objects position in a conventional array since the phase of the object is not local to the phase center of the array but geometrically spread. By using the composite signal this problem does not occur.

In the distributed array context another problem that occurs is that due to multipath, it is hard to attribute a given signal to a specific scatter. Thus as is shown in Figure 4. by grouping elements into closely spaced clusters, local directional estimates of targets can be formed at low bandwidth and signals compared across the distributed elements once bright points are identified and correlated. This method also alleviates the computational burden of the method by only processing bright points that occur in the scene from multiple cluster viewpoints. We assume that relative synchronized time information will be exchanged by all RF observing points.

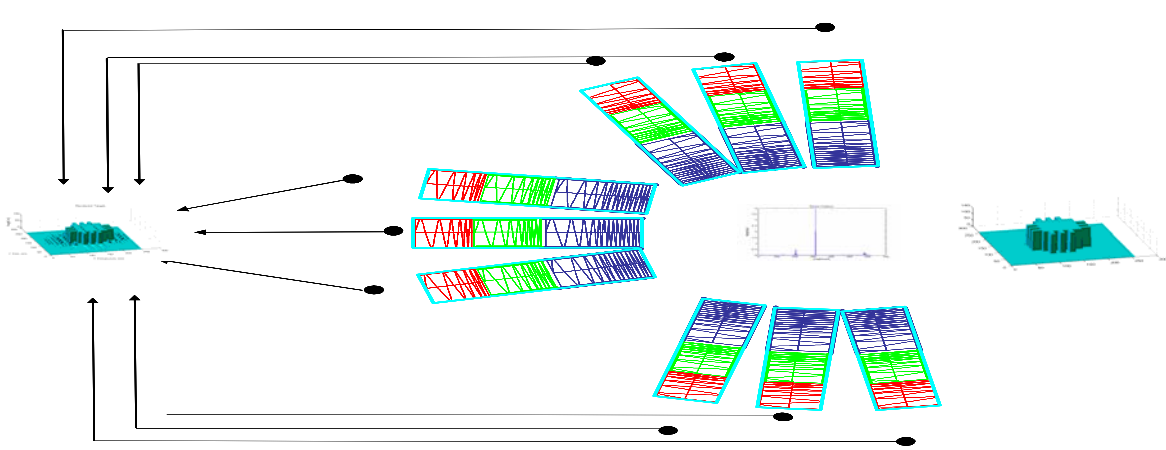

Figure 3 Composite chirp in terms of phased array.

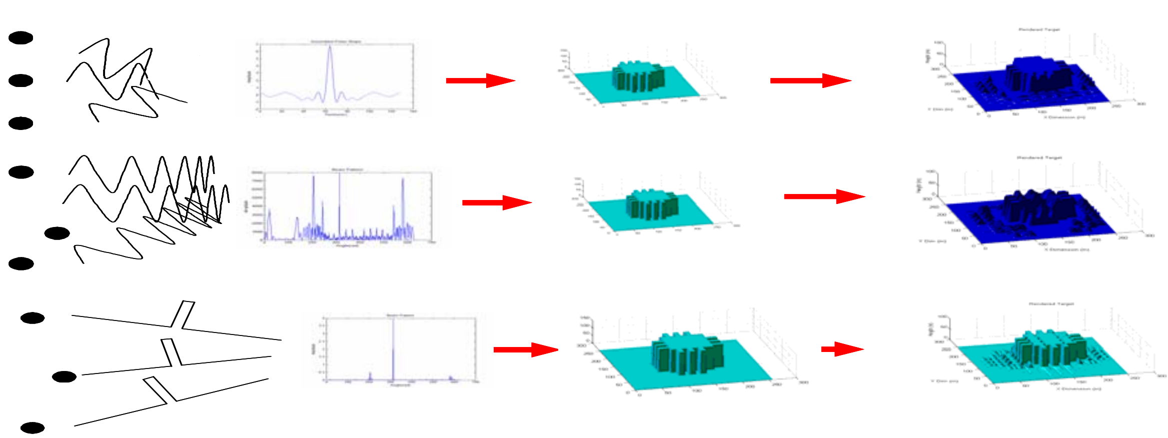

Figure 4 Effects of array and integrated chirp aproach.

III. Results

Figure 5 shows the signal testing procedure. We first showed how the composite chirp method works with a linear array and reasonably little bandwidth. As we can see from Figure 5a, this method gives reasonable results with the composite representation of the test target having good fidelity. We next made the array non-uniform with relatively low instantaneous bandwidth as is shown in Figure 5b. We can see that this approach does not allow for high resolution on the test target since grating lobe effects start to occur. Finally we simulate a non-uniform array with relatively high bandwidth and we are able to replace the irregularities in the array with the increased resolution provided by the collective bandwidth of the composite chirp to obtain the total response of the target. as is shown in Figure 5c.

IV. Conclusion

We have shown how a high resolution pulse can be created through multiple narrowband chirp signals to improve spatial resolution in antenna arrays. This approach allows high resolution 3 Dimensional imaging response from targets in situations that were not previously possible due to antenna characteristics, frequency allocations, or computational burdens.

References

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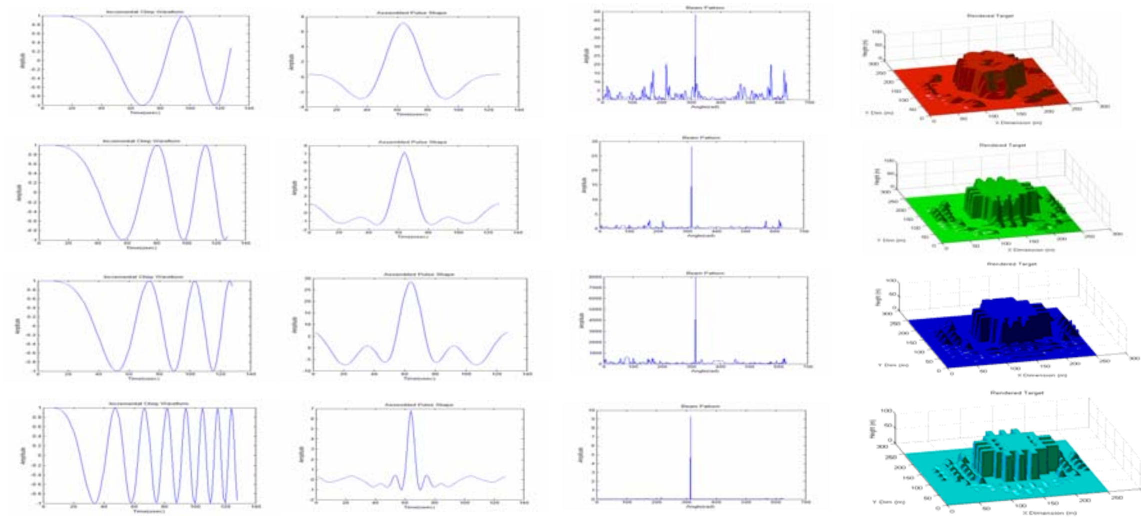
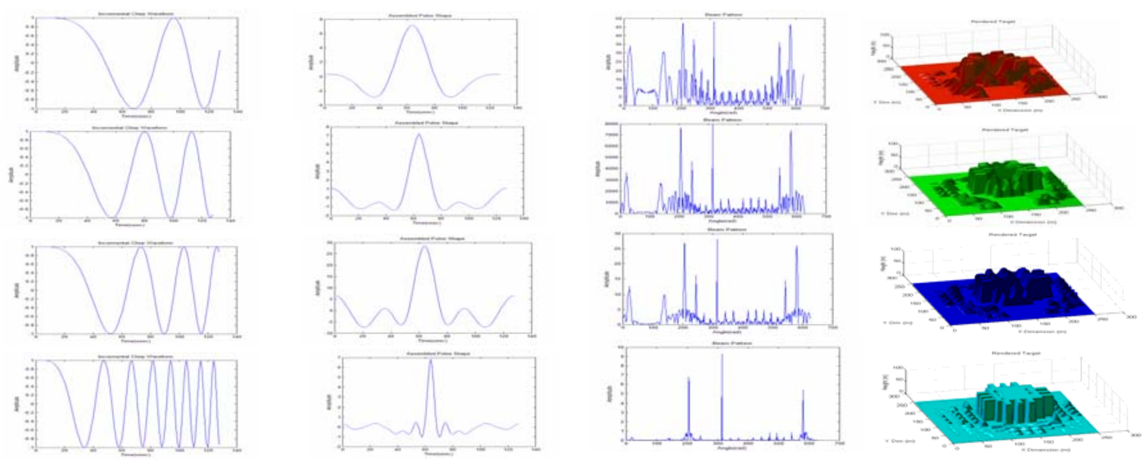
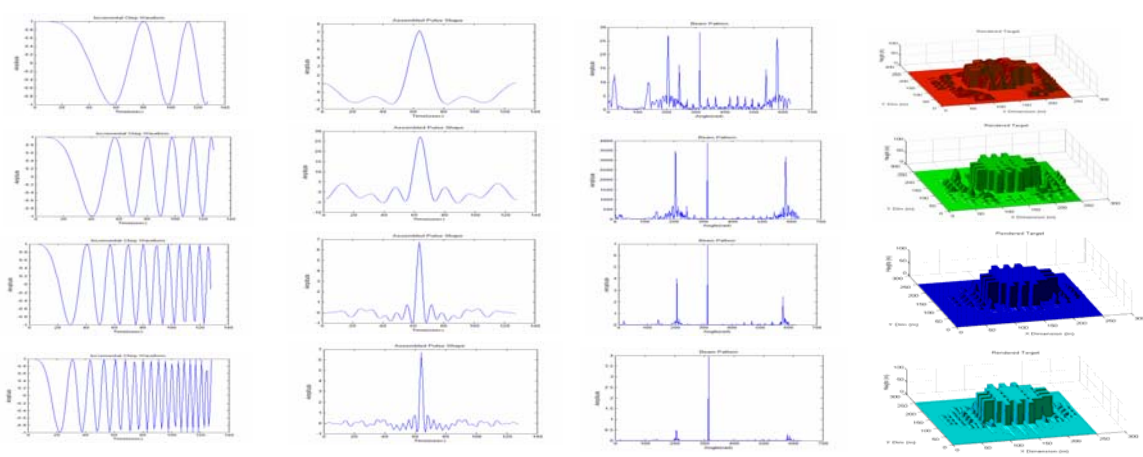
$f_n(t)$ $h_n(t)$ $h(\tau)$ $k(\tau)$



Figures 5a Uniform Array Low Bandwidth



Figures 5b Nonuniform Array Low Bandwidth



Figures 5c Nonuniform Array Wide Bandwidth