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SAR Ambiguous Range Suppression

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ABSTRACT

Pulsed Radar systems suffer range ambiguities, that is, echoes from pulses transmitted at different times arrive at the receiver simultaneously. Conventional mitigation techniques are not always adequate. However, pulse modulation schemes exist that allow separation of ambiguous ranges in Doppler space, allowing easy filtering of problematic ambiguous ranges.

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FOREWORD

As Sandia National Laboratories becomes involved with designing ever longer-range and higher-velocity systems, including orbital systems, the problem of ambiguities in range and Doppler become more problematic. The technique discussed herein was postulated as one possible mitigation scheme.

1 INTRODUCTION & BACKGROUND

Pulsed radar systems emit sequences of pulses towards a target location and receive their echoes, timing them to infer target range. However, when an echo from a recent pulse coincides with an echo from an earlier pulse, from a more distant target, then a range ambiguity exists for the radar. This is illustrated in figure 1. Imaging radar systems such as Synthetic Aperture Radar (SAR) might exhibit ghosts in a manner similar to those from double-exposing a photographic camera film.

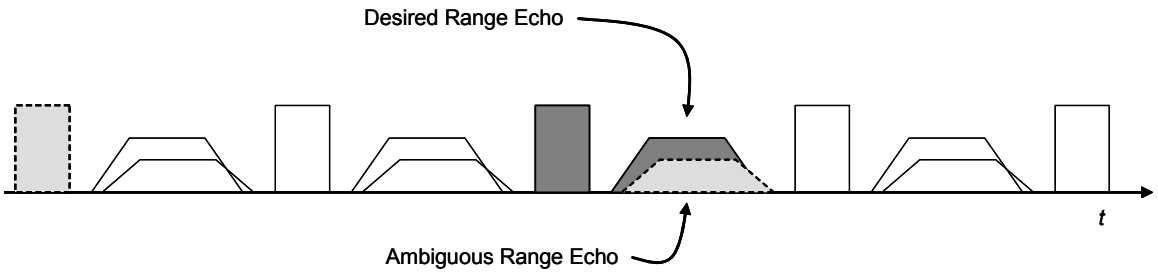

Figure 1. Radar pulse train exhibiting ambiguous range echoes.

Alternatively, sometimes a radar must operate at a high enough Pulse Repetition Frequency (PRF) that the desired echo is from a pulse emitted earlier than the most recent pulse emitted. This is common in long-range high-velocity SAR systems, such as space orbital SAR systems. In such a case an undesired ambiguous range might be nearer than the actual desired range to be interrogated.

A common practice for a radar designer is to choose an antenna design that substantially attenuates echoes at angles that correspond to ambiguous ranges when the main beam is directed towards the target scene of interest. Often this is sufficient to adequately mitigate ambiguous range returns, but not always. Sometimes an echo at an ambiguous range is sufficiently strong to overcome the antenna's sidelobe attenuation, as is the case with an earth nadir echo. When antenna sidelobe attenuation is not adequate, additional mitigation procedures are needed.

A common practice for some systems is to stagger or vary the PRF to identify the correct target range from an ambiguous set. Algorithms are discussed by Chen, et al.,[1] Shar, et al.,[2] and Skolnik.[3] This is common in radars that are designed to detect isolated targets, such Moving Target Indicator (MTI) radars. SAR systems' images are usually unacceptably degraded by varying the PRF in this manner, consequently this technique is of limited utility for SAR systems.

Modulating the transmitted signal on a pulse-to-pulse basis with a unique identifying modulation such as a phase code will identify the correct pulse for an echo, and hence help resolve any range ambiguity. Algorithms are discussed by Kramer[4], and Anderson.[5] However the energy from the ambiguous ranges will not be eliminated but rather just redistributed in a manner to raise the background noise of the demodulated signal,

thereby reducing the fidelity of the data. A SAR image will exhibit elevated background noise, perhaps to the point of washing out the image.

Using alternately positive and negative chirp rates for a Linear FM chirp waveforms on successive pulses is discussed by Mittermayer and Martinez,[6] but the authors acknowledge that utility is mainly for range-ambiguous point targets and not for "extended targets".

Selecting a specific PRF can sometimes be employed to mitigate a specific problematic echo, such as a nadir echo, but this limits allowable operating geometries. Geometric limits are discussed by Curlander and McDonough,[7] and Doerry.[8]

Often, only specific ambiguous ranges are problematic. For SAR systems the ambiguous ranges most near to the desired range generally benefit the least from antenna pattern attenuation. For orbital systems it is often the nadir echo that is most problematic.

Ideally, what is required is the separation of desired echoes from problematic undesired echoes at ambiguous ranges. Doppler radars such as SAR do allow a degree of freedom to accomplish this.

2 OVERVIEW & SUMMARY

Doppler radar systems such as SAR allow a degree of freedom to separate the desired echo from an undesired ambiguous range echo. A pulse-to-pulse phase modulation can be employed to shift echoes from an undesired range to regions of the Doppler spectrum that facilitate their attenuation by conventional digital filtering techniques. Since the desired range is known, as is its pulse phase modulation, these can be accommodated in a manner so as to have no negative effect for the desired range echo.

Consequently the desired range is separated in Doppler space from the undesired ambiguous range. This allows the undesired ambiguous range to be suppressed without affecting the desired range echo.

3 DETAILED ANALYSIS

Consider a transmitted radar signal of form

$$X_T(t,k) = A(t - t_k)\exp j(\Phi(t - t_k) + \phi_k) \tag{1}$$

where

t = time,
k = pulse index number,
t_k = reference time for the kth pulse,
$A(t - t_k)$ = pulse envelope for the kth pulse,
$\Phi(t - t_k)$ = pulse dynamic phase function for the kth pulse, and
ϕ_k = phase offset for the kth pulse. (2)

The variation of ϕ_k with index k will constitute pulse-to-pulse phase modulation.

Subsequent to this, the radar receiver receives an echo from the desired range, and from an ambiguous range.

$$X_R(t,k) = a_m X_T(t - t_m, k - m) + a_n X_T(t - t_n, k - n) \tag{3}$$

where

m = the desired pulse index to receive,
n = the undesired ambiguous range index received,
a_m = gain/attenuation factor for mth pulse echo, and
a_n = gain/attenuation factor for nth pulse echo.

Consequently

$$X_R(t,k) = \begin{bmatrix} a_m A(t - t_m - t_{k-m})\exp j(\Phi(t - t_m - t_{k-m}) + \phi_{k-m}) \\ + a_n A(t - t_n - t_{k-n})\exp j(\Phi(t - t_n - t_{k-n}) + \phi_{k-n}) \end{bmatrix} \tag{4}$$

Since the two echoes are presumed to coincide, and are otherwise identical except for gain factors and phase offset ϕ ,

$A(t - t_m - t_{k-m}) = A(t - t_n - t_{k-n})$, and
$\Phi(t - t_m - t_{k-m}) = \Phi(t - t_n - t_{k-n})$. (5)

A radar receiver matched to the desired range will yield an output signal

$$X_V(k) = \int_A X_R(t,k) \exp j(-\Phi(t - t_m - t_{k-m}) - \phi_{k-m}) dt \,. \tag{6}$$

The integral subscript A denotes integration over the envelope of the received echo. This yields

$$X_V(k) = \int_A a_m dt + \int_A a_n \exp j(\phi_{k-n} - \phi_{k-m}) dt \,. \tag{7}$$

The first integral is the desired response that is located at zero Doppler independent of index k. The second integral is the undesired response that we wish to separate from the first integral in Doppler. This is accomplished by choosing phase ϕ_k such that $(\phi_{k-n} - \phi_{k-m}) = \pi\, k$ or equivalent. We cause this by selecting

$$\phi_k = \phi_{k-(m-n)} + \pi\, k \,, \tag{8}$$

or alternatively

$$\phi_k = \phi_{k-(m-n)} + \pi\,(k+1). \tag{9}$$

Since either of these would work equivalently, we adopt the notation

$$\phi_k = \phi_{k-(m-n)} + \pi\, k + [\pi] \tag{10}$$

where $[\pi]$ denotes an optional constant.

3.1 Adjacent pulses

For example, if desired pulse m and undesired pulse n differ by one pulse, then

$$\phi_k = \phi_{k-1} + \pi\, k + [\pi] \qquad \text{for } |m-n| = 1. \tag{11}$$

A sequence of ϕ_k that would accomplish this is

0, 0, π, π, 0, 0, π, π, 0, 0, π, π, 0, 0, π, π, … (12)

This would cause the modulo-2π difference phase $(\phi_{k-n} - \phi_{k-m})$ to be

π, 0, π, 0, π, 0, π, 0, π, 0, π, 0, π, 0, π, 0, ... (13)

or

0, π, 0, π, 0, π, 0, π, 0, π, 0, π, 0, π, 0, π, ... (14)

depending on whether $m - n = \pm 1$.

In either case, this algorithm modulates the ambiguous range signal to the Doppler fold-over frequency, well away from the desired range signal at Doppler zero frequency. This is illustrated in figure 2.

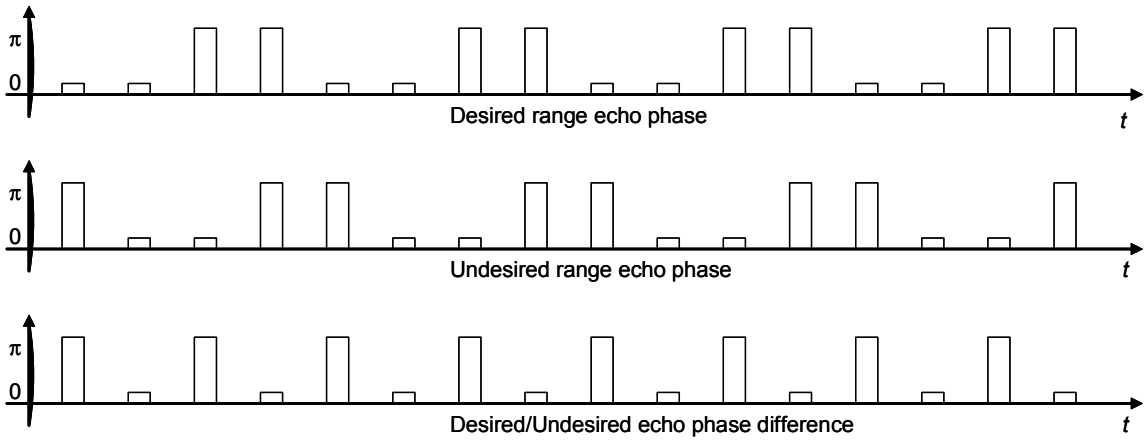

Figure 2. Illustration of ambiguous range echo phase modulation for $m - n = \pm 1$.

Furthermore, this modulation scheme will similarly modulate any ambiguous range to the Doppler fold-over frequency for which $|m - n|$ is an odd integer.

3.2 Non-adjacent pulses

Consider $(m - n) = 2$. In this case we desire

$$\phi_k = \phi_{k-2} + \pi\, k + [\pi]. \tag{15}$$

A sequence of ϕ_k that would accomplish this is

$$0, 0, 0, \pi, 0, 0, 0, \pi, 0, 0, 0, \pi, 0, 0, 0, \pi, \ldots \tag{16}$$

This would cause the modulo-2π difference phase $(\phi_{k-n} - \phi_{k-m})$ to be

$$0, \pi, 0, \pi, 0, \pi, 0, \pi, 0, \pi, 0, \pi, 0, \pi, 0, \pi, \ldots \tag{17}$$

This is illustrated in figure 3.

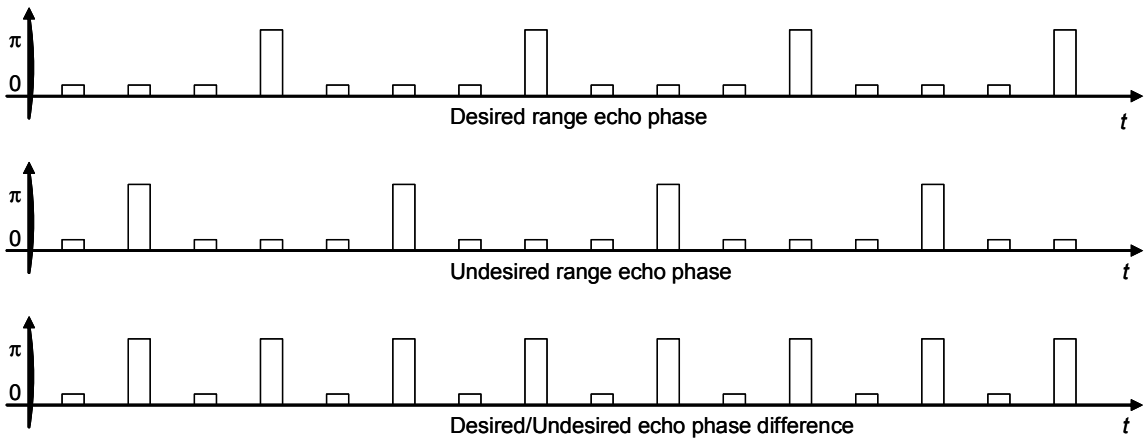

Figure 3. Illustration of ambiguous range echo phase modulation for $(m-n)=2$.

Notably, any ambiguous range for which $|m-n| = 2+4p$ for some integer p would be similarly modulated.

More generally, if $(m-n)=K$, for an even K, then we desire

$$\phi_k = \phi_{k-K} + \pi\, k + [\pi]. \tag{18}$$

A sequence of ϕ_k that would accomplish this is

$$\phi_k = \begin{cases} (k/K)\pi & k = even \\ 0 & k = odd \end{cases}. \tag{19}$$

For such a sequence we validate

$$\phi_k - \phi_{k-K} = \begin{cases} \pi & k = even \\ 0 & k = odd \end{cases}. \tag{20}$$

Furthermore, any ambiguous range for which $|m-n| = K+2Kp$ for some integer p would be similarly modulated.

4 CONCLUSIONS

Essential elements of this technique include

- Echoes from ambiguous ranges can be separated in Doppler.
- When separated in Doppler, ambiguous ranges can be filtered from the desired response.
- Pulse-dependent modulation can be employed to achieve the Doppler separation of an ambiguous range from the desired response.
- Pulse phase coding is one such modulation scheme that can be employed to achieve the Doppler separation of an ambiguous range from the desired response.
- Pulse phase codes are given herein to separate the desired return from any problematic ambiguous range.

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