Nearly Orthogonal, Doppler Tolerant Waveforms and Signal Processing for Multi-mode Radar Applications

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PRESENTATION OUTLINE

- **Research Problem**
- **Significance of this Research**
- **An Overview on MIMO Radar /Waveform-agile radar**
- **A Review on Radar Ambiguity Function, Orthogonal Waveform, Target Resolution, and Doppler Tolerance**
  - **Nearly Orthogonal Transmit and Receive Waveforms Design**
  - **High Resolution Imaging / Advanced Processing**
- **Joint SAR and GMTI Processing**
- **Conclusion**

PROBLEM STATEMENT

I. **Design Nearly Orthogonal (on both Transmit and Receive), Doppler Tolerant Waveforms**
   - **The key issue is that designing waveforms that should remain orthogonal on receive has not been addressed fully by the researchers.**

II. **Demonstrate Non-interfering Measurement Capabilities (for High Resolution Imaging) of these Waveforms**

III. **Demonstrate Multi-mode (Joint SAR and GMTI Processing) Processing Capability of these Waveforms**

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SIGNIFICANCE OF THIS RESEARCH

1. Design and analysis of radar waveforms to satisfy nearly orthogonality on both transmit and receive

- In MIMO Radar settings, it is assumed that waveforms should remain orthogonal on both transmit and receive; However, because of unknown Doppler shifts and delays caused by target's motion, receive waveforms don't stay nearly orthogonal

- This research provides a solution to designing waveforms that should remain nearly orthogonal on both transmit and receive

- Allows waveform-agile sensing and exploitation (more discussion on this to follow)

SIGNIFICANCE OF THIS RESEARCH

2. **Non-interfering, waveform diverse measurements for high resolution imaging**
   - Guey and Bell reported that single waveform type makes it difficult to distinguish two or more closely spaced targets in delay and Doppler
   - It was shown that by using diverse waveforms, enhanced delay-Doppler measurements is possible
   - The key assumption was that waveforms should not interfere with each other
   - **Our proposed waveforms allow non-interfering measurement and processing by using diverse, orthogonal waveforms**

**J-C. Guey., and M. Bell. "Diversity Waveform Sets for Delay-Doppler Imaging," IEEE Transaction on Information Theory, Volume 44, No.4, July 1998.

SIGNIFICANCE OF THIS RESEARCH

3. Joint SAR and GMTI Processing

- Joint processing of SAR and GMTI is an important research problem. The waveforms characteristics for SAR and GMTI are different– GMTI Processing requires a high PRF; However, high PRF results in increased range ambiguity and processing burden in SAR imaging.

- Our proposed waveforms offer a solution to this complex problem

- ***The Key enabler in our approach is that we can separate the GMTI and SAR waveforms at the receiver (by applying their spreading code) and process them accordingly***

PUBLICATIONS

1. U. Majumder, M.R. Bell, and M. Rangaswamy, "A Novel Approach for Designing Diversity Radar Waveforms that are Orthogonal on Both Transmit and Receive,**" in *Proceedings of IEEE Radar Conference*, May 2013, Ottawa, Canada.**

2. U. Majumder, M.R. Bell, and M. Rangaswamy, "Design and Analysis of Radar Waveforms to Satisfy Transmit and Receive Orthogonality" ***IEEE Transactions on Aerospace and Electronic Systems (Revised version to be submitted by Dec. 3, 2014)***

3. U. Majumder, M.R. Bell, and M. Rangaswamy, "Diverse, Waveforms and Processing Techniques for Joint GMTI and SAR Exploitation," **in *Proceedings of IEEE Radar Conference*, May 2014, Cincinnati, Ohio, USA.**

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A BRIEF OVERVIEW ON MIMO RADAR

I. Multiple-input Multiple-output (MIMO) Radar
   - Originated from MIMO communication (David Goldfein)
   - Multiple transmitters can transmit diverse, orthogonal signals/waveforms
   - Received signals should be orthogonal as well in order to exploit all advantages over the traditional radar

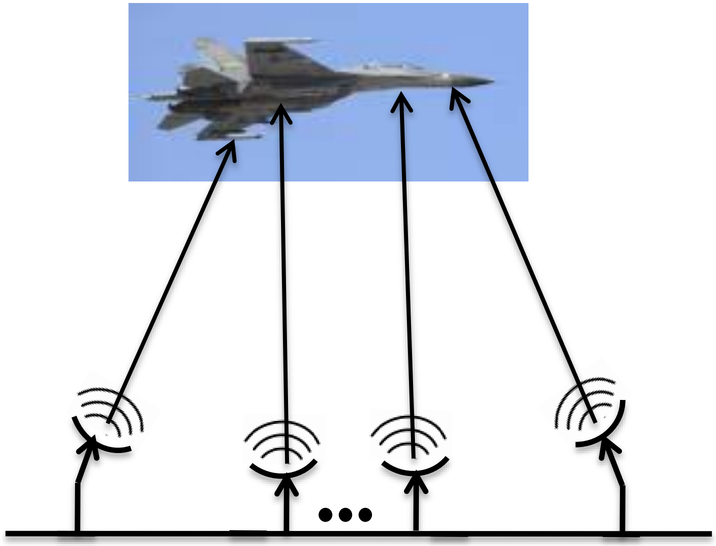
II. Two types of MIMO radar
   - MIMO radar with colocated antennas
   - MIMO radar with widely-separated antennas / "Statistical MIMO Radar"/ Multistatic Radar

III. References:

- V. S. Cherniak. "MIMO radars. What are they?" 7th European Radar Conference, 2010, France
- Rick Blum. "Statistical MIMO Radar". Lehigh University. AFOSR Talk.
- J. Li and P. Stoica, MIMO Radar Signal Processing. New York, NY: John Wiley and Sons, 1st ed., 2009.

A BRIEF OVERVIEW ON MIMO RADAR..

I. MIMO radar and angular spread
- **Angular spread-** variability of the signals received across the array
- A **high angular spread** implies **low correlation** between target backscatter



II. MIMO radar offers the potential for significant gains:

- **Detection/estimation performance through diversity gain**
- **Resolution performance through spatial resolution gain**

*** For MIMO, we will have less power density on transmit (No Beamforming on transmit)

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MIMO RADAR WAVEFORM RESEARCH

- **Designing transmit orthogonal waveforms are relatively simple**
  - We can use orthogonal Walsh-Hadamard code on transmit signal to make the waveforms orthogonal to each other

- **Designing Waveforms that remain orthogonal on receive is complex**

  - A solution to this problem will allow separating the receive signals before processing data on entire array.

- **Most of the current research focused on optimizing receive waveforms to increase SNR or resolution or clutter cancellation**
  - ➢ No emphasis on how to design physical waveforms structure that should remain orthogonal on receive
  - ➢ Many authors proposed MIMO radar waveform design based on frequency diversity, code, polarizations etc.

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Waveform Agility

- Defined as the ability of a radar system to adapt and change its waveforms while operating
- Waveform agility often provides improved performance over non-adaptive waveforms radar systems in a dynamic or heterogeneous environment.
- The reason is that waveform-agile radar systems can change various radar operating parameters, including frequency, pulse repetition frequency (PRF), polarization, and bandwidth based on operating conditions of the environment.
- For example, to detect fast moving targets, a radar system has to operate in high PRF mode. By contrast, a low PRF rate is necessary to detect slow moving targets

A. Nehorai, F. Gini, M. Greco, A. Papandreou-Suppappola, and M. Rangaswamy, “Introduction to the issue on adaptive waveform design for agile sensing and communication," IEEE Journal of Selected Topics in Signal Processing, vol. 1, June 2007.

PRESENTATION OUTLINE

- ✓ Research Problem
- ✓ Significance of this Research
- ✓ A Brief Overview on MIMO Radar/Waveform-agile Radar
- ► A Review on Radar Waveform
  - Mismatched Filter and the Ambiguity Function
  - Orthogonal Waveform
  - Target Resolution
  - Doppler Tolerance
- Transmit and Receive Waveforms Design
- Advanced Processing
- Joint SAR and GMTI Processing
- Conclusion

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LITERATURE SEARCH AND OUR CONTRIBUTION

[1] N. Levanon and E. Mozeson, Radar Signals. Harlow, England: Wiley-IEEE Press, 1st ed., 2004.
[2] C. Cook and M.Bernfeld, Radar Signals: An Introduction to Theory and Application. New York, NY: Academic Press, 1st ed., 1967.
[3] August W. Rihaczek. "Principles of High-Resolution Radar" Artech House Radar Library, 1996

We defined and illustrated following terms in the case of a Matched-filter Radar :

1. ε - orthogonality of two waveforms
2. **Ambiguity Function and Target Resolution**
3. **Ambiguity Function and Doppler Tolerance**

MISMATCHED FILTER AND THE AMBIGUITY FUNCTION

Consider, a radar system transmits a signal $s(t)$. Then the received signal resulting from the radar return from a moving point target can be written as

$$r(t) = (ae^{i\phi})s(t-\tau_0)e^{i2\pi\upsilon_0 t}$$

where τ_0 is the time delay due to propagation of the signal to and from the target, υ_0 is Doppler shift resulting from the radial motion of the target with respect to the radar, and $ae^{i\phi}$ is the complex amplitude of a point scatterer.

Assume we process with a matched filter (MF) matched to $s(t)$ with delay τ and Doppler shift υ. If we sample at $t=T$, then,

$$h_{\tau\upsilon}(t) = MF_T\{s(t-\tau)e^{i2\pi\upsilon t}\}$$

$$= s^*(T-t-\tau)e^{-i2\pi\upsilon_0(t-T)}$$

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MISMATCHED FILTER AND THE AMBIGUITY FUNCTION

The output of the matched filter sampled at $t = T$ can be written as

$$
\begin{aligned}
O_T(\tau, \upsilon) &= r(t) * h_{\tau\upsilon}(t)\,\big|_{t=T} \\
&= a e^{i\phi} \int_{-\infty}^{\infty} s(t-\tau_0) e^{i2\pi\upsilon_0 t} s^*(t-\tau) e^{-i2\pi\upsilon t} dt \\
&= a e^{i\phi} \int_{-\infty}^{\infty} s(t-\tau_0) s^*(t-\tau) e^{-i2\pi(\upsilon-\upsilon_0)t} dt
\end{aligned}
$$

MISMATCHED FILTER AND THE AMBIGUITY FUNCTION

Making the substitution $p = t - \tau_0,$ *from which it follows that* $t = p + \tau_0$ *and* $dt = dp.$
Then we can write,

$$O_T(\tau, \upsilon) = ae^{i\phi} \int_R s(p) s^*\left(p - (\tau - \tau_0)\right) e^{-i2\pi(\upsilon - \upsilon_0)(p + \tau_0)} dp$$

$$= ae^{i\phi} . e^{-i2\pi(\upsilon - \upsilon_0)\tau_0} \int_R s(p) s^*\left(p - (\tau - \tau_0)\right) e^{-i2\pi(\upsilon - \upsilon_0)p} dp$$

$$= ae^{i\phi} . e^{-i2\pi(\upsilon - \upsilon_0)\tau_0} \beta_s\left(\tau - \tau_0, \upsilon - \upsilon_0\right)$$

where

$$\beta_s(\tau, \upsilon) := \int_R s(t) s^*(t - \tau) e^{-i2\pi\upsilon t} dt = \chi_s(\tau, -\upsilon)$$

and

$$\chi_s(\tau, \upsilon) := \int_{-\infty}^{\infty} s(t) s^*(t - \tau) e^{+i2\pi\upsilon t} dt$$

MISMATCHED FILTER AND THE AMBIGUITY FUNCTION

- If we think of a radar as an imaging system, then the ambiguity function is the point spread function or impulse response of the system

- To obtain high-resolution images, we will require sharp ambiguity functions.

- Then one might say that the radar target resolution research primarily becomes a radar waveform design problem

MISMATCHED FILTER AND THE AMBIGUITY FUNCTION

I. Asymmetric ambiguity function:

$$\chi(\tau,\nu)=\int_{-\infty}^{\infty} s(t)s^{*}(t-\tau)\exp(i2\pi\nu t)dt$$

II. Ambiguity surface: Modulus of ambiguity function

- To plot ambiguity function, we will use the convention

We will talk about Linear Frequency Modulated (LFM) waveform

- Monograph by Cook and Bernfeld provides comprehensive treatment of various waveforms
- P.M. Woodward first introduced asymmetric form of ambiguity function

AMBIGUITY FUNCTION OF LFM SIGNAL

Consider an LFM signal be:

$$
\begin{aligned}
s(t) &= \mathrm{rect}\left(\frac{t}{T}\right)\exp\left[i2\pi\left(f_0 t + \frac{1}{2}\alpha t^2\right)\right] \\
&= \mathrm{rect}\left(\frac{t}{T}\right)\exp\left(i\pi\alpha t^2\right)\exp\left(i2\pi f_0 t\right) \\
&= u(t)\exp(i2\pi f_0 t)
\end{aligned}
$$

where

f_0 : is carrier frequency

α : is chirp rate

T : is pulse width

$u(t) = \mathrm{rect}\left(\frac{t}{T}\right)\exp(i\pi\alpha t^2)$: is the complex envelope

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AMBIGUITY FUNCTION OF LFM SIGNAL

Now, ambiguity function of an LFM signal can be defined as:

$$\chi_s(\tau,\nu)=\int_{-\infty}^{\infty} s(t)s^*(t-\tau)e^{i2\pi\nu t}dt$$

$$=\int_{-\infty}^{\infty}\text{rect}\left(\frac{t}{T}\right)e^{i\pi\alpha t^2}\text{rect}\left(\frac{t-\tau}{T}\right)e^{-i\pi\alpha(t-\tau)^2}.e^{i2\pi\nu t}dt$$

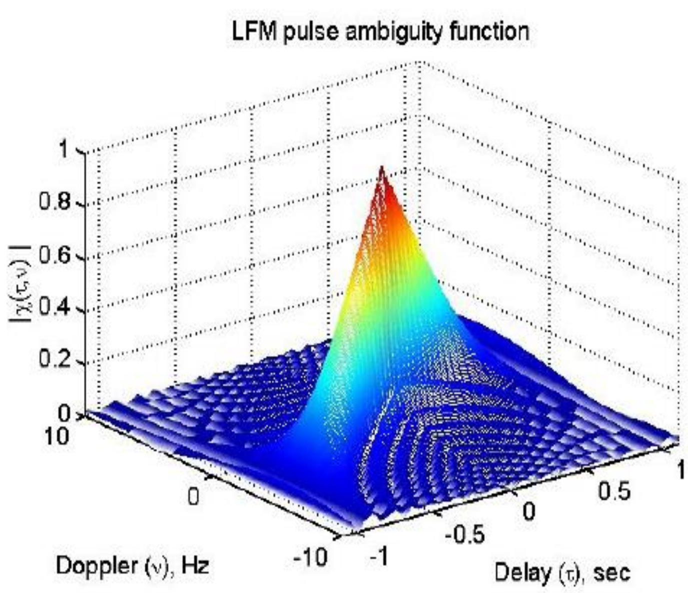
$$=e^{-i\pi\alpha\tau^2}\int_{-\infty}^{\infty}\text{rect}\left(\frac{t}{T}\right)\text{rect}\left(\frac{t\text{-}\tau}{T}\right).e^{i2\pi(\nu+\alpha\tau)t}dt$$

After further simplification, closed form solution for ambiguity function of an LFM signal is given by:

$$\chi_s(\tau,\nu)=(T-|\tau|)\text{sinc}\left[(\nu+\alpha\tau)(T-|\tau|)\right]e^{i\pi\nu\tau}.e^{i\pi(\nu+\alpha\tau)T}$$

for $|\tau|\le T,$ zero elsewhere.

AMBIGUITY FUNCTION OF LFM SIGNAL



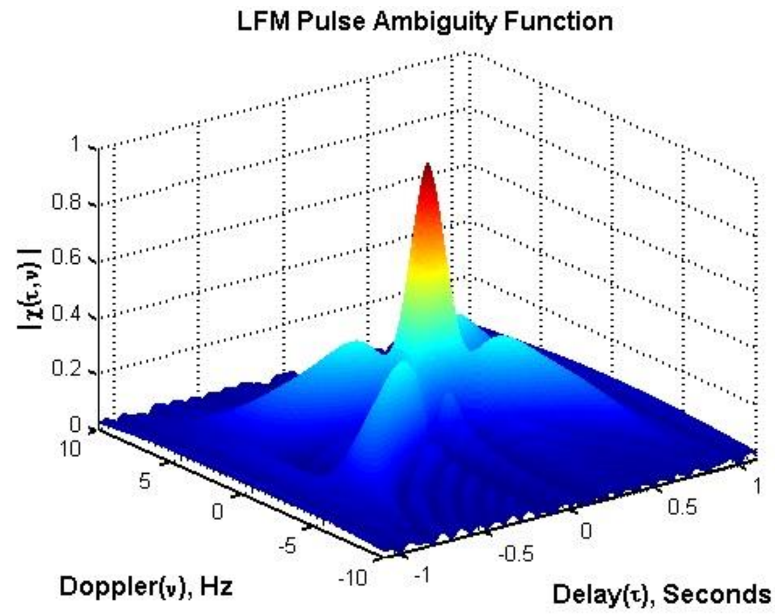


Figure (a): LFM Ambiguity Function With one chirp rate

Figure (b): LFM ambiguity function with two chirp rates

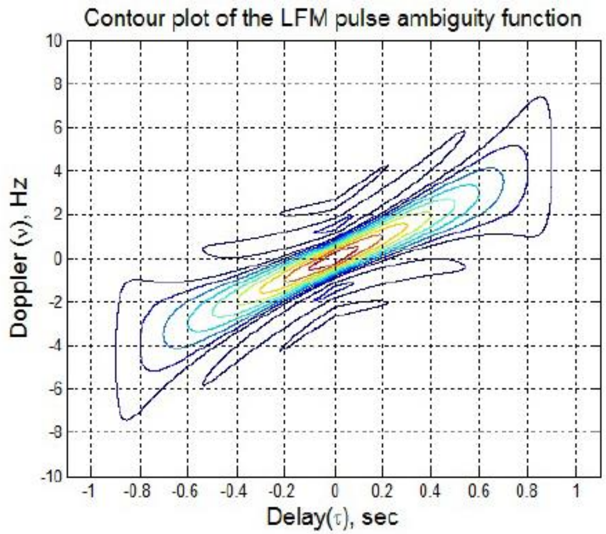


Figure (c): Contour plot of LFM ambiguity function with one chirp rate

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THE CROSS-AMBIGUITY FUNCTION

The cross-ambiguity function (CAF) of two finite energy signals $s_1(t)$ and $s_2(t)$ defined as

$$\chi_{s_1,s_2}(\tau,\upsilon) = \int_{-\infty}^{\infty} s_1(t) s_2^*(t) e^{i2\pi\upsilon t} dt$$

The ability to distinguish a signal $s_1(t)$ from a time-delayed, Doppler-shifted version of a signal $s_2(t)$ is given by the metric

$$d_{\tau,\upsilon}\big(s_1(t), s_2(t)\big) = \int_{-\infty}^{\infty} \left| s_1(t) - s_2(t-\tau) e^{-i2\pi\upsilon t} \right|^2 dt$$

$$= E_{s_1} + E_{s_2} - 2\mathrm{Re}\left\{\chi_{s_1 s_2}(\tau,\upsilon)\right\}$$

From above expression, we can say that two signals can be separated Easily when cross-ambiguity (cross-correlation) between them is small and this will happen when signals are orthogonal or nearly orthogonal

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MEASURING APPROXIMATE ORTHOGONALITY OF TWO WAVEFORMS USING CROSS-AMBIGUITY

In theory, when two signals are orthogonal to each other, their inner product is zero. This is equivalent to their time cross-correlation function being equal to zero at lag zero.

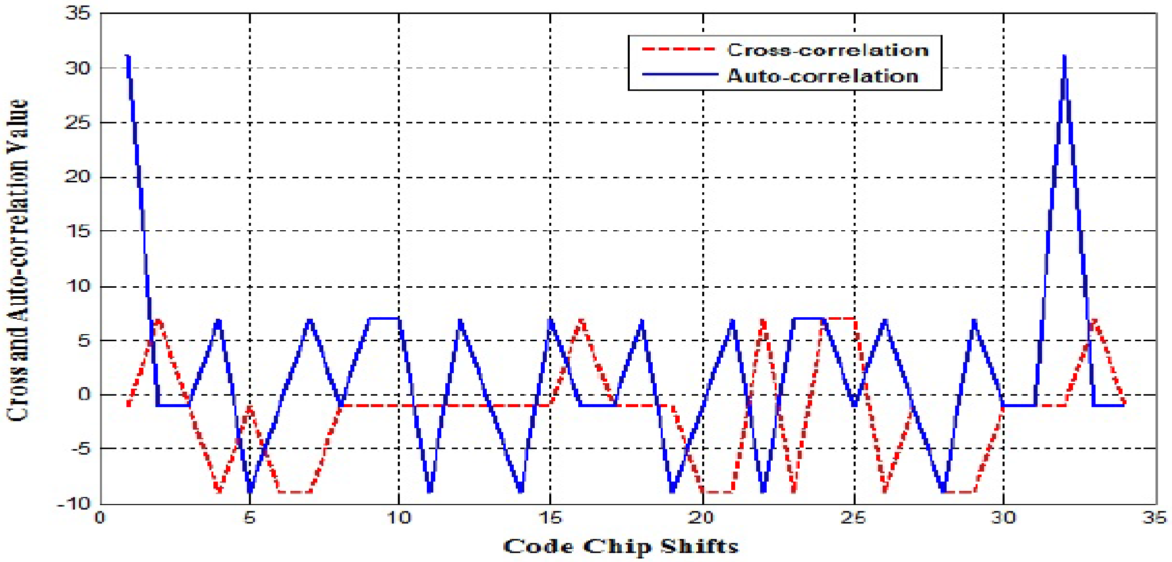

Fig. 2.6. Cross and auto-correlation of length 31 Gold codes when synchronization mismatch occurs. In perfect synchronization (i.e. when transmit and receive codes are completely orthogonal), autocorrelation should exhibit highest peak value at the middle and zero everywhere; similarly, cross-correlation should exhibit zero everywhere. However, often perfect synchronization is unachievable.

MEASURING APPROXIMATE ORTHOGONALITY OF TWO WAVEFORMS

In this research, we define two waveforms are nearly orthogonal or $\varepsilon -$ orthogonal when following criteria is met :

$$\frac{\text{Cross - ambiguity of signal } s_1 \text{ and signal } s_2}{\text{Energy of signal } s_1 \text{. Energy of signal } s_2} \leq \varepsilon,$$

or,
$$\operatorname*{Max}_{\tau,\upsilon} \frac{|\chi_{s_1 s_2}(\tau,\upsilon)|\text{^}2}{E_1 E_2} \leq \varepsilon$$

Or equivalently,
$$\operatorname*{Max}_{\tau,\upsilon} \frac{\left|\int_{-\infty}^{\infty} s_1(t) s_2(t-\tau) e^{i2\pi\upsilon t} dt\right|\text{^}2}{E_1 E_2} \leq \varepsilon$$

where E_1 is the energy in signal $s_1(t)$ and E_2 is the energy in signal $s_2(t)$

MEASURING APPROXIMATE ORTHOGONALITY OF TWO WAVEFORMS

Often the threshold value (i.e. ε) is specified in dB appropriate for operating conditions.

Effectively, ε-orthogonality implies that the interference resulting from $s_2(t)$ does not significantly affect the output of a matched-filter for $s_1(t)$, in the presence of all possible delay and Doppler shifts, at least for ε sufficiently small.

AMBIGUITY FUNCTION AND DELAY-DOPPLER RESOLUTION OF MATCHED FILTER RADAR

In its simple definition, radar target resolution is the ability to determine the presence of a second target in the presence of another. From a processing view point, two criteria must be satisfied to resolve a target from radar measurement:

(i) a target's signature output peak should be as narrow as possible in delay-Doppler because wider output peak will increase uncertainty by adding closely-spaced target’s signature and

(ii) target's signature should not be obscured by clutter or other interference sources

August W. Rihaczek. “Principles of High-Resolution Radar”
Artech House Radar Library, 1996

AMBIGUITY FUNCTION AND DELAY-DOPPLER RESOLUTION OF MATCHED FILTER RADAR

- The Ambiguity Function can be used to analyze delay-Doppler resolution of matched filter radar.

- The Ambiguity Function can guide us designing waveforms to demonstrate a reasonably narrow main lobe target response and low sidelobe levels, and thus resolving multiple targets both in delay and Doppler

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AMBIGUITY FUNCTION AND DELAY-DOPPLER RESOLUTION OF MATCHED FILTER RADAR

Consider two targets with responses, delays, and Doppler represented by $(a_1, \tau_1, \upsilon_1)$ and $(a_2, \tau_2, \upsilon_2)$ respectively. Now, combined matched filter output for these two targets can be expressed as :

$$O_T(\tau, \upsilon) = a_1 e^{i\phi_1} . e^{-i2\pi(\upsilon-\upsilon_1)\tau_1} \beta_s(\tau-\tau_1, \upsilon-\upsilon_1) + a_2 e^{i\phi_2} . e^{-i2\pi(\upsilon-\upsilon_2)\tau_2} \beta_s(\tau-\tau_2, \upsilon-\upsilon_2)$$

$$= a_1 e^{i\phi_1} . e^{-i2\pi(\upsilon-\upsilon_1)\tau_1} \chi_s(\tau-\tau_1, -(\upsilon-\upsilon_1)) + a_2 e^{i\phi_2} . e^{-i2\pi(\upsilon-\upsilon_2)\tau_2} \chi_s(\tau-\tau_2, -(\upsilon-\upsilon_2))$$

AMBIGUITY FUNCTION AND DELAY-DOPPLER RESOLUTION OF MATCHED FILTER RADAR

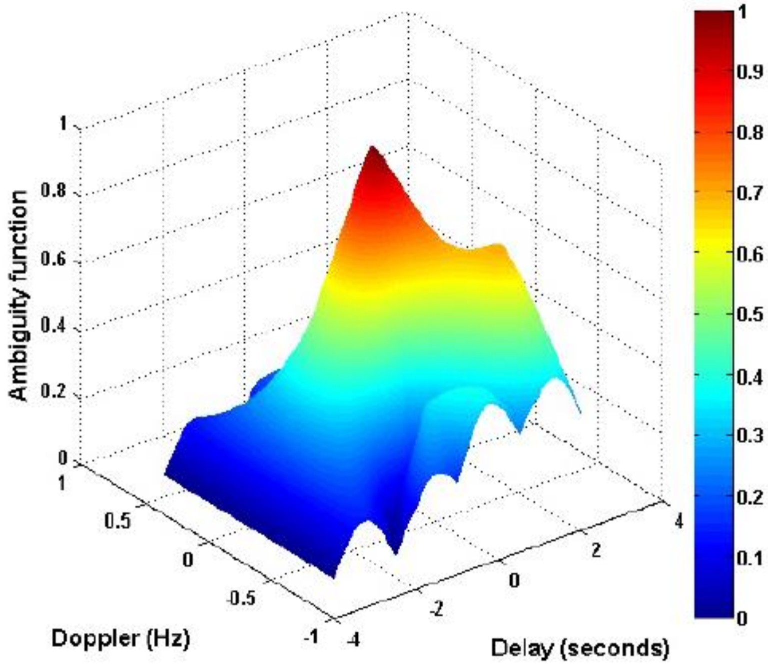

Fig. : 3D delay-Doppler response of two targets close to each otl

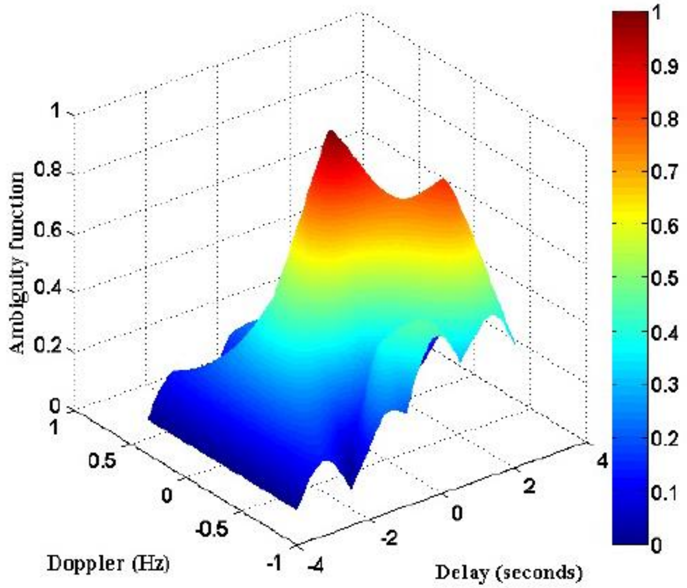

Fig. 2.9. 3D delay-Doppler response of two targets close to each other after redesigning the waveforms to provide better resolution. Both targets are now more resolvable.

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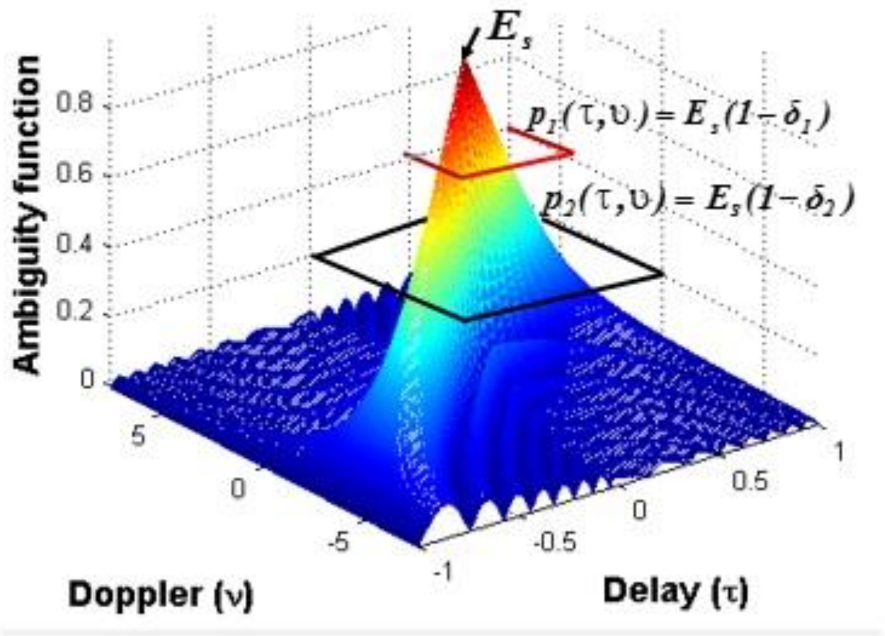
MEASURING DOPPLER TOLERANCE

We know that the amplitude of the matched-filter output for a received signal mismatched on delay (τ) and Doppler(υ) is given by $|\chi_s(\tau,\upsilon)|$.

Figure below visualize the $|\chi_s(\tau,\upsilon)|$ of a linear frequency modulated waveform.



The peak value, which occurs at $(\tau,\upsilon)=(0,0)$ is the E_s that is the energy in the signal $s(t)$. We define two planes at the ambiguity surface as follows:

$$p_1(\tau,\upsilon)=E_s(1-\delta_1);\quad p_2(\tau,\upsilon)=E_s(1-\delta_2)$$

MEASURING DOPPLER TOLERANCE

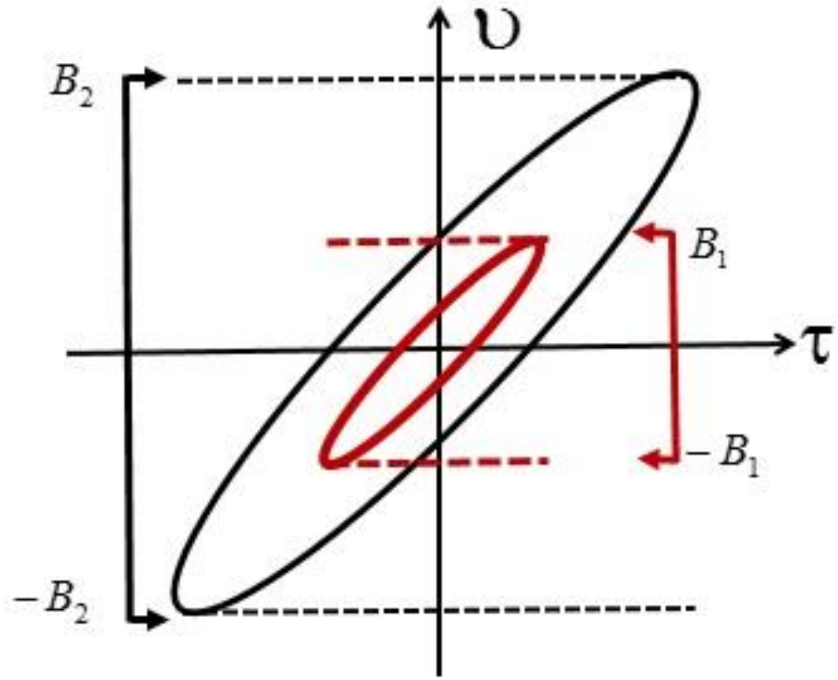


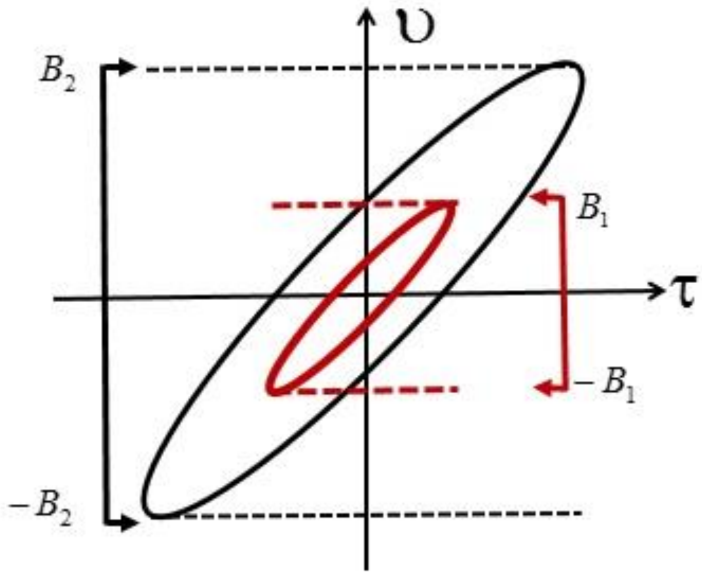
Fig. Level sets for two planes cut through the ambiguity function of an LFM waveform. Here, B_1 and B_2 are bandwidths and $B_1 < B_2$

If we look at where the intersection of these planes with $|\chi_s(\tau, \upsilon)|$ we get the level sets (i.e., points that are at level $E_s(1 - \delta_k)$, $k = 1, 2..$ on the function $|\chi_s(\tau, \upsilon)|$)

MEASURING DOPPLER TOLERANCE

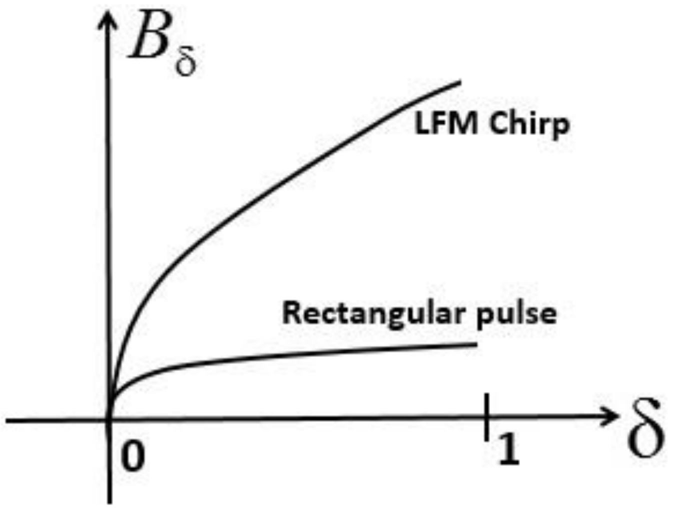
Now if the return signal has a Doppler shift $\upsilon \in [-B_1, B_1]$ then the *matched filter's* amplitude output (matched to the original non-Doppler shifted signal $s(t)$) will be greater than or equal to $E_s(1-\delta_1)$.

Similarly, if $\upsilon \in [-B_2, B_2]$ we know that the absolute value of the matched filter output will be greater or equal to $E_s(1-\delta_2)$



MEASURING DOPPLER TOLERANCE

Let, B_δ be the bandwidth over which the matched filter output is greater than or equal to $E_s(1-\delta)$. We can say in general, as δ grows greater (i.e., if we allow a lower matched filter magnitude output) B_δ will grow bigger. The rate of this growth will depend on the waveform type.

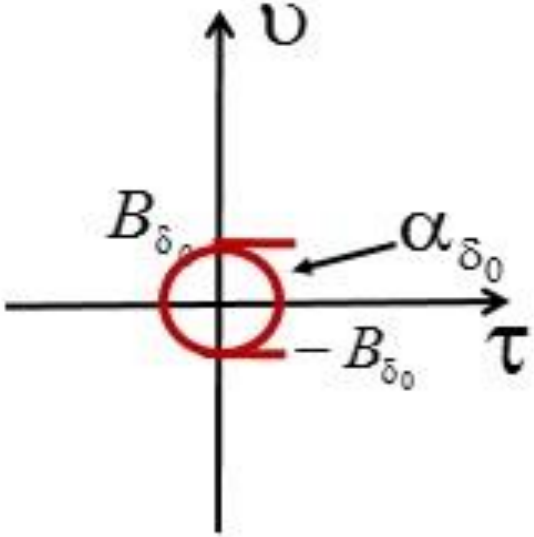


The LFM waveform has a significant matched filter response over a broad range of frequencies $[-B_\delta, B_\delta]$, where as, for the non-Doppler tolerant waveform this range is much smaller.

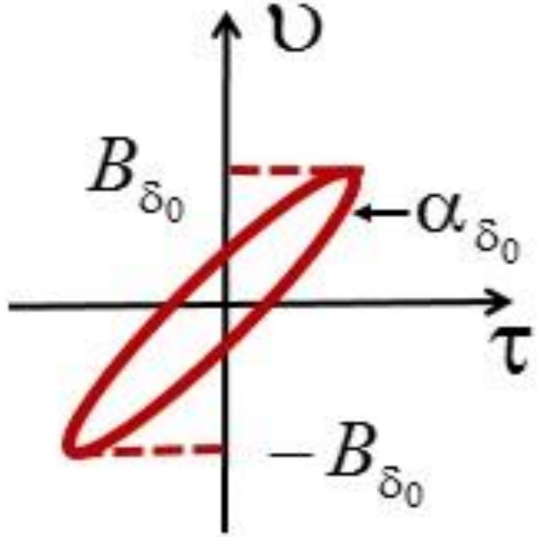
Definition: Doppler Tolerance

Let $|\chi_s(\tau, \upsilon)|$ be the absolute value of the ambiguity function of the signal $s(t)$. Let α_δ be the innermost connected level set corresponding to amplitude $E_s(1-\delta)$ out of the matched filter. Then we say that $s(t)$ is B_δ Doppler tolerant, and its Doppler tolerance is characterized by the curve (δ, B_δ) as δ varies from 0 to 1.

AMBIGUITY FUNCTION AND DOPPLER TOLERANT WAVEFORMS



Costas Sequence



LFM

We are interested in the closest level set surrounding the origin $(\tau, \upsilon) = (0,0)$. At this location, the waveform that covers more frequency bandwidth, it can accomodate more Doppler frequency shift for good output performance and hence more Doppler tderant.

RADAR AMBIGUITY FUNCTION

SUMMARY

✓ **We introduced the ideas and tools used to describe**

- **Approximate Orthogonality of two radar waveforms**
  - We named $\varepsilon - \mathit{Orthogonality}$ of two waveforms
- **Radar target resolution**
- **Radar waveform Doppler tolerance**
  - We named B_δ *Doppler* Tolerant

We have seen that, all of these ideas can be described in terms of ambiguity functions and cross-ambiguity functions in the case of a matched-filter radar.

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PRESENTATION OUTLINE

- ✓ Research Problem
- ✓ Significance of this Research
- ✓ A Brief Overview on MIMO Radar/Waveform-agile Radar
- ✓ A Review on Radar Ambiguity Function, Orthogonal Waveform, Target Resolution and Doppler Tolerance
- ► Nearly Orthogonal Transmit and Receive Waveforms Design
  - Technical Approach
  - Direct Sequence Spread Spectrum (DSSS)
  - Cross-ambiguity Function of Coded LFM
  - Experiments
  - Results and Analysis
  - Summary on Orthogonal Waveforms
- High Resolution Imaging / Advanced Processing
- Joint SAR and GMTI Processing
- Conclusion

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ORTHOGONAL WAVEFORM DESIGN

TECHNICAL APPROACH

Orthogonality Requirement:

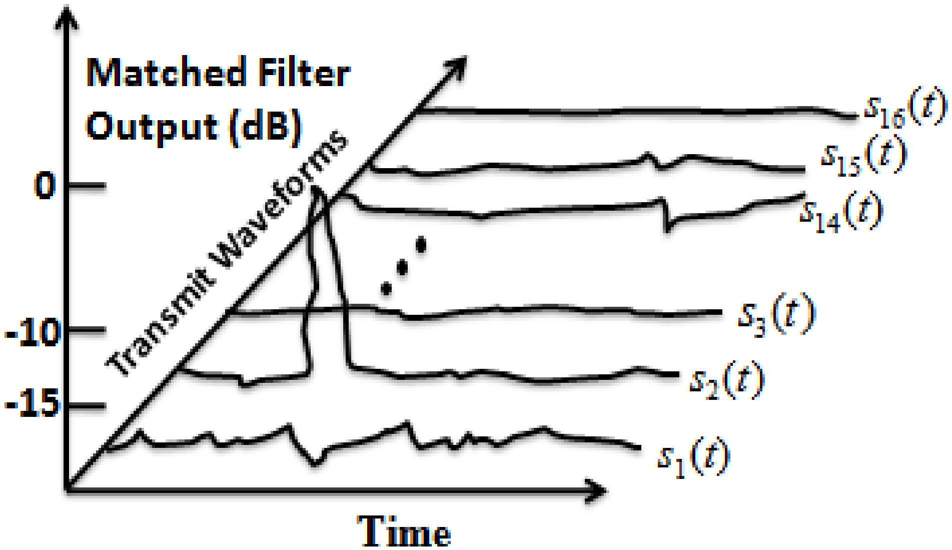
- Suppose we have ‘N’ transmit elements (say N=16)
- We can assign an orthogonal code to each of the transmitted waveforms
- After receive, we will correlate the received signal with a transmitted signal and check energy level. Non-orthogonal (coded) signals will exhibit the highest energy after the matched filter (correlation).
- We employ Spread Spectrum Technique for coding. So, this approach is similar to CDMA technique

Doppler Tolerant Requirement:

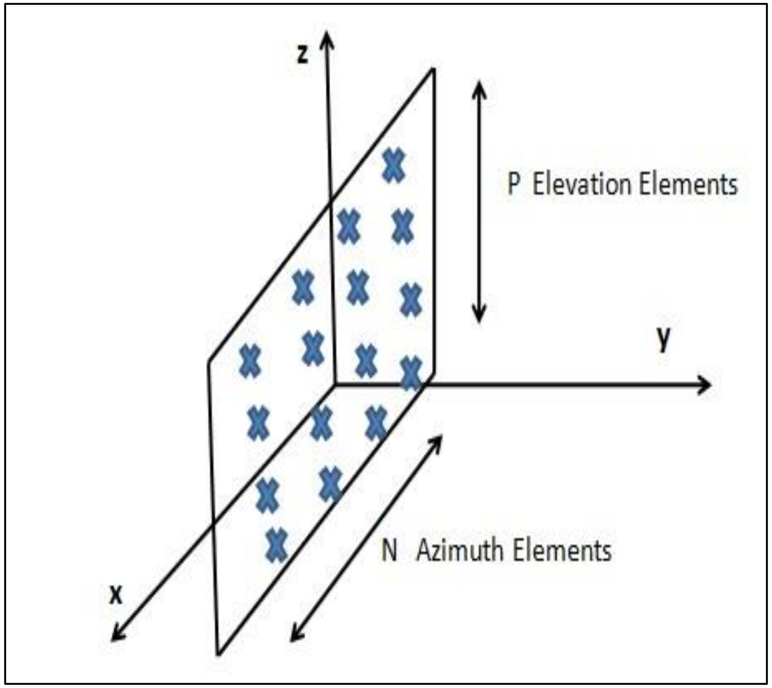
- We use LFM waveform which is known to have good Doppler tolerant property

ORTHOGONAL WAVEFORM DESIGN

TECHNICAL APPROACH (2)



Pictorial depiction of matched filter response of transmit signal $s_2(t)$ with signals $s_1(t)$, $s_2(t)$ ... $s_{16}(t)$. All of the transmit signals are coded with unique orthogonal spread spectrum code. After receive, when matched filter is performed, only $s_2(t)$ will provide maximum return.



MIMO Phased Array

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ORTHOGONAL WAVEFORM DESIGN

LITERATURE RESEARCH AND OUR CONTRIBUTION

We found two records related to this research area:

- S. Hengstler, D. Kasilingam, **"A NOVEL CHIRP MODULATION SPREAD SPECTRUM TECHNIQUE FOR MULTIPLE ACCESS"** Proceedings of the IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA 2002), vol. 1, pp. 73-77, September 2002
- **N. Levanon , Radar Signals"**
  - **Sidelobe reduction using coded waveform**

Our Contribution:

We provided a unique solution to Waveform design for Waveform-agile radar applications where *received waveforms can be nearly orthogonal as well as the transmitted waveforms*

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DIRECT SEQUENCE SPREAD SPECTRUM (DSSS)

I. Spread spectrum is pioneering technique implemented in modern wireless communication (CDMA)

II. It works very well in high interference environment

III. Information signal is expressed as:

$$A(t) = \sum_{-\infty}^{\infty} a_n P(t - nT_b)$$

where

$a_n : \pm 1$

$P(t)$: rectangular pulse of duration T_b

DIRECT SEQUENCE SPREAD SPECTRUM (2)

Now, $A(t)$ is multiplied by the coded signal

$$C(t) = \sum_{n=-\infty}^{\infty} c_n P(t - nT_c)$$

to produce the product or spreaded signal

$$B(t) = A(t).C(t)$$

where

c_n : is binary PN code of ± 1's

$P(t)$: is the rectangular pulse of duration T_c

DIRECT SEQUENCE SPREAD SPECTRUM (3)

The **Product signal or spreaded signal** is then modulated with a carrier signal and transmitted.

$$T_x(t) = A(t)C(t).\cos(2\pi f_c t)$$

Received signal is the transmitted signal and interference.

$$R_x(t) = A(t)C(t).\cos(2\pi f_c t) + I(t)$$

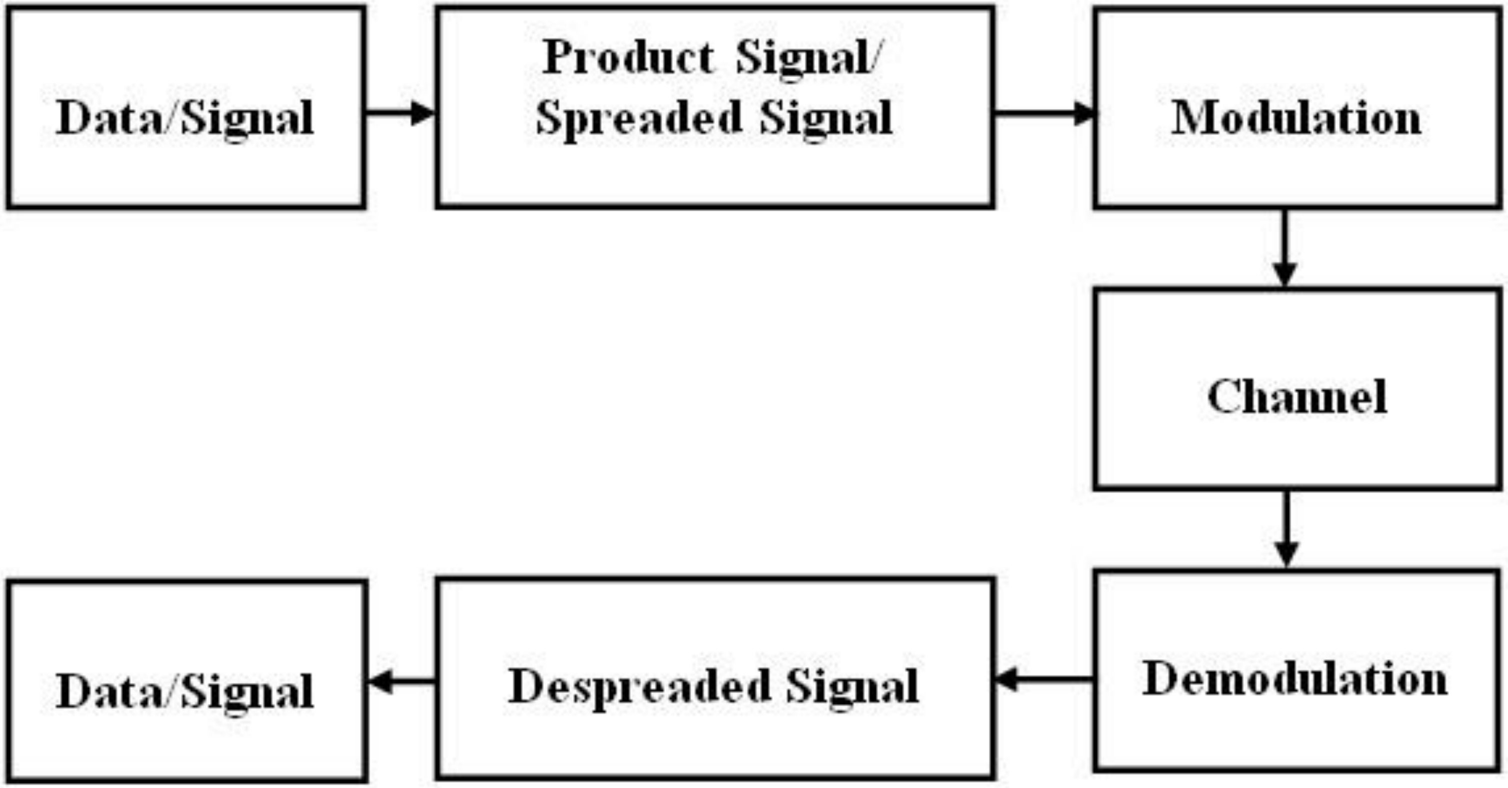
In demodulation process, received signal is multiplied by code signal

$$D_x(t) = R_x(t)C(t)$$

Above process is **"spectrum despreading"** and output of this process is our original information signal.

$$D_x(t) = A(t)$$

DIRECT SEQUENCE SPREAD SPECTRUM BLOCK DIAGRAM



CROSS-AMBIGUITY FUNCTION OF CODED LFM SIGNAL

Let, an LFM signal be: $s(t) = e^{i\pi\alpha t^2} .1_{[0\ T]}(t)$

Now, define two direct sequence spread spectrum coded LFM signals as follows:

$$s_1(t) = \sum_{m}^{M-1} C_m P(t - mT_C).e^{i\pi\alpha_1 t^2}$$

$$s_2(t) = \sum_{n}^{N-1} D_n P(t - nT_C).e^{i\pi\alpha_2 t^2}$$

where

C_m : *First Code Sequence*

D_n : *Second Code Sequence (different from* C_m*)*

T_C : *Chip Time*

α_1, α_2 : *Different Chirp Rates*

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CROSS-AMBIGUITY FUNCTION OF CODED LFM SIGNAL (2)

Now cross-ambiguity function of $s_1(t)$ and $s_2(t)$ can be expressed as:

$$\chi_{s_1,s_2}(\tau,\nu)=\int_R s_1(t)s_2^*(t-\tau)e^{i2\pi\nu t}dt$$

$$=\int_R\left(\sum_{m=0}^{M-1}C_mP(t-mT_c).e^{i\pi\alpha_1 t^2}\right).$$

$$\left(\sum_{n=0}^{M-1}D_nP(t-nT_c-\tau).e^{i\pi\alpha_2(t-\tau)^2}\right)^*.e^{i2\pi\nu t}dt$$

$$=\sum_{m=0}^{M-1}\sum_{n=0}^{M-1}C_mD_n^*\int_R P(t-mT_c)P^*(t-nT_c-\tau).e^{i\pi[\alpha_1t^2-\alpha_2(t-\tau)^2]}.e^{i2\pi\nu t}dt$$

CROSS-AMBIGUITY FUNCTION OF CODED LFM SIGNAL (3)

$$\text{Let, } f(m,n,\tau,\nu) :=$$

$$\int_R P(t-mT_c)P^*(t-nT_c-\tau).e^{i\pi[\alpha_1 t^2-\alpha_2(t-\tau)^2]}.e^{i2\pi\nu t}dt$$

Therefore, Cross-ambiguity function of spread spectrum coded LFM signal is given by:

$$\chi_{s_1,s_2}(\tau,\nu) = \sum_{m=0}^{M-1}\sum_{n=0}^{M-1} C_m D_n^*.f(m,n,\tau,\nu)$$

We call above equation *Spread Spectrum Coded LFM (SSCL)* signaling.

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ORTHOGONAL WAVEFORM DESIGN

Spread Spectrum Coded LFM (SSCL) Signaling:

Important properties of the SSCL signaling have been listed below. The proofs for these properties are straightforward.

1. *Cross-ambiguity property of SSCL signaling:* When the codes C_m and D_n^* are orthogonal, $\chi_{s_1,s_2}(\tau,\nu) \cong 0$. This property implies that matched filter response of a transmitted signal s_1 with a received signal s_2 will be small if s_2 does not have the same code as the s_1 (i.e. cross-ambiguity function will be almost zero when C_m and D_n^* are orthogonal).

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Spread Spectrum Coded LFM (SSCL) Signaling:

2. *Auto-ambiguity property of SSCL signaling:* When codes C_m and D_n^* are the same, $\chi_{s_1,s_2}(\tau,\nu)$ will provide the highest return. This property implies that matched filter response of a transmitted signal s_1 with a received signal s_2 will be the highest if s_2 has the same code as the s_1 (this also implies that $s_1 = s_2$).

3. *Code property of SSCL signaling:* The type of code such as Walsh-Hadamard code, Gold code, Kasami code etc will influence the cross-ambiguity or auto-ambiguity response (i.e. degree of orthogonality of the received signal).

ORTHOGONAL WAVEFORM DESIGN

Spread Spectrum Coded LFM (SSCL) Signaling:

4. ***Code length property of SSCL signaling:*** The length of code such as 8, 16, 32, or 512 will also determine degree of orthogonality of the received signal. Furthermore, the length of code will also determine bandwidth expansion of the SSCL signal and hence increased resolution.

5. ***Time bandwidth property of SSCL signaling:*** Increased time bandwidth product can be achieved by SSCL signaling. Bandwidth expansion provides the unique capability of this SSCL signal. First of all, after despreading the code, we can get our original LFM signal back and get our usual LFM signal resolution (Doppler tolerant). Secondly, by processing the coded signal we can get ultra-high resolution to separate closely spaced targets.

6. ***Bandwidth reduction property of SSCL signaling:*** We can use biorthogonal codes to reduce the bandwidth (by a factor of half) requirement of SSCL signals. This does not affect the performance of SSCL signal significantly.

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EXPERIMENT

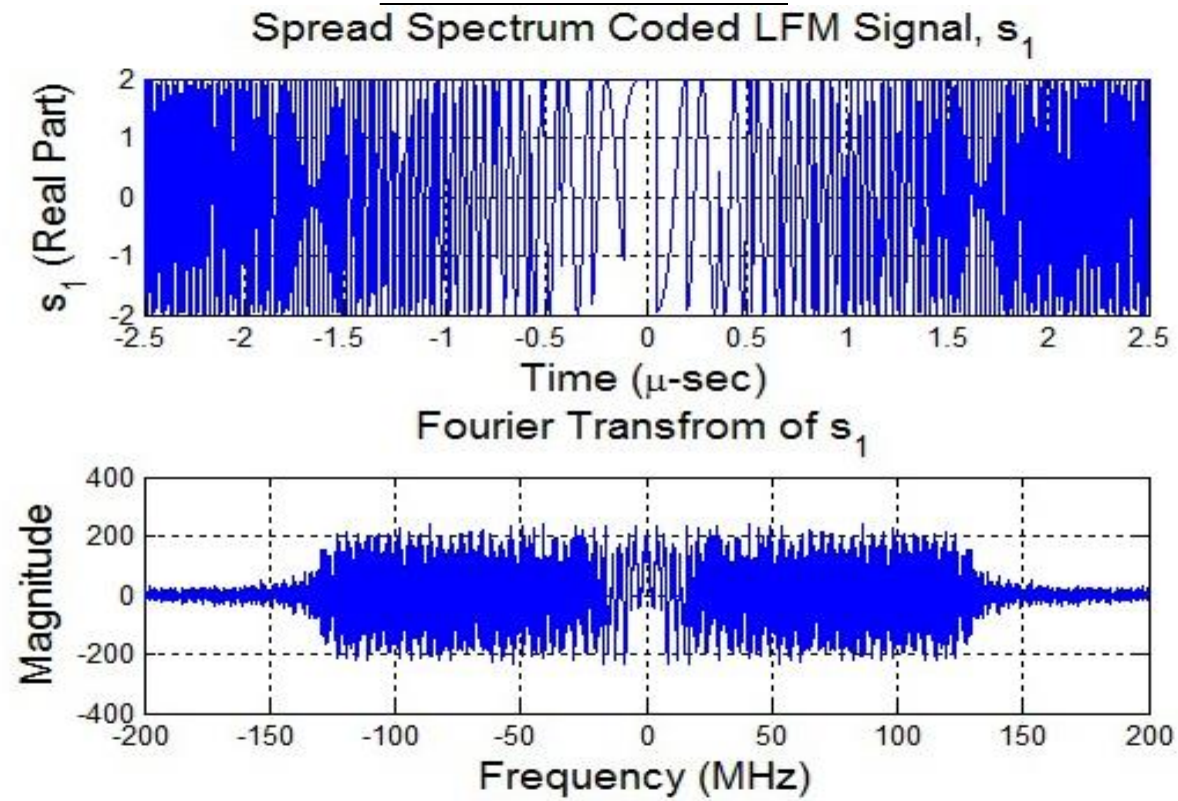
Parameters	Values
Bandwidth (B)	4,36,130,260,1000 MHz
First Pulse Duration(TP_1)	10 μsec
Second Pulse Duration (TP_2)	10 μsec
First Pulse Chirp Rate(α_1)	$(1 * B)/TP_1$
Second Pulse Chirp Rate (α_2)	$(-2 * B)/TP_2$
First Pulse Code Length (NC_1)	1,8,32,64,256
Second Pulse Code Length (NC_2)	1,8,32,64,256

Experimental parameters used to examine SSCL signaling

$$BW = \frac{1}{TC_1} + \frac{1}{TP_1}$$

;TC1=TP1/NC1

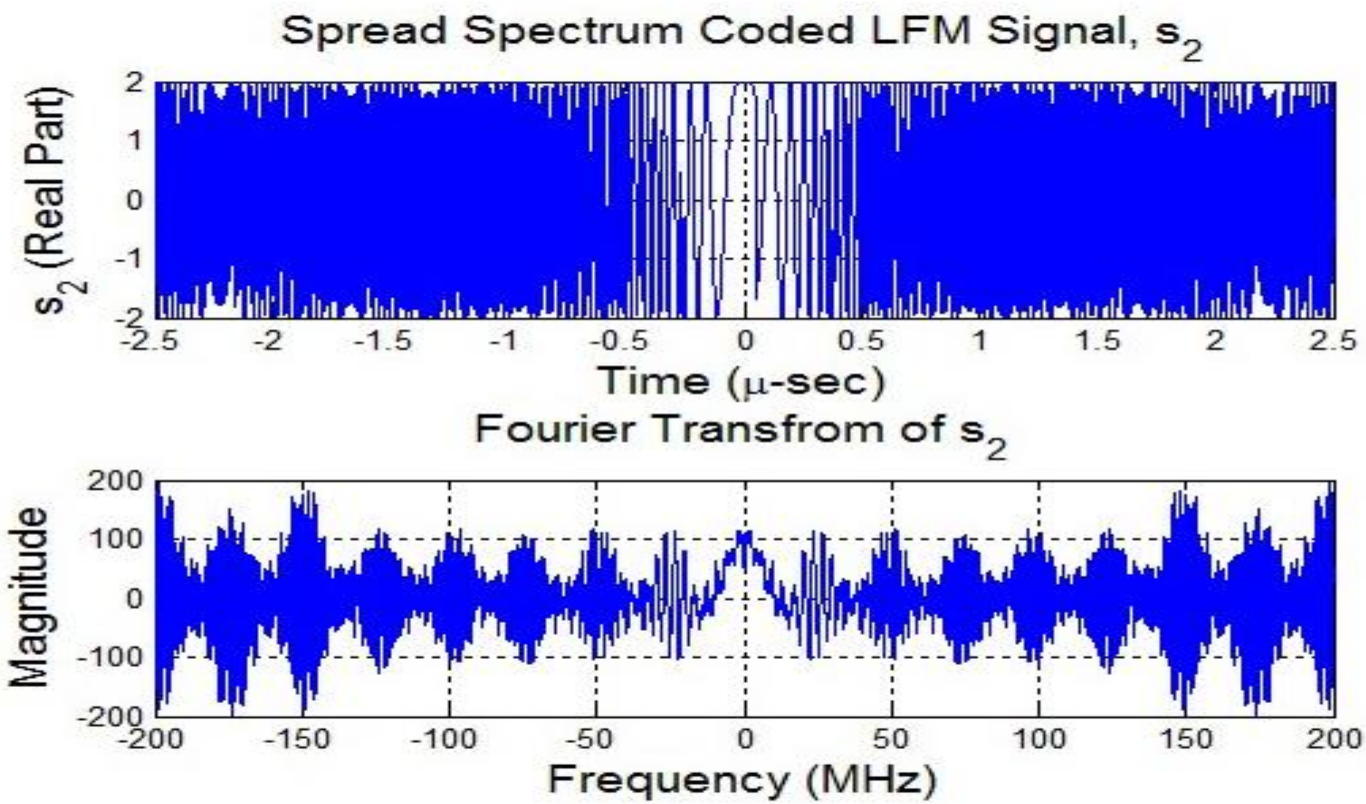
EXPERIMENT



Spread spectrum coded LFM signal s_1 and corresponding Fourier transform. Chirp rates used were, $\alpha_1 = (1 * B)/TP_1$ and $\alpha_2 = (-1 * B)/TP_1$, where B is the bandwidth of the LFM signal after applying spread spectrum code, TP_1 is duration of the signal. Walsh-Hadamard code of length 64 has been used to spread the LFM signal.

ORTHOGONAL WAVEFORM DESIGN

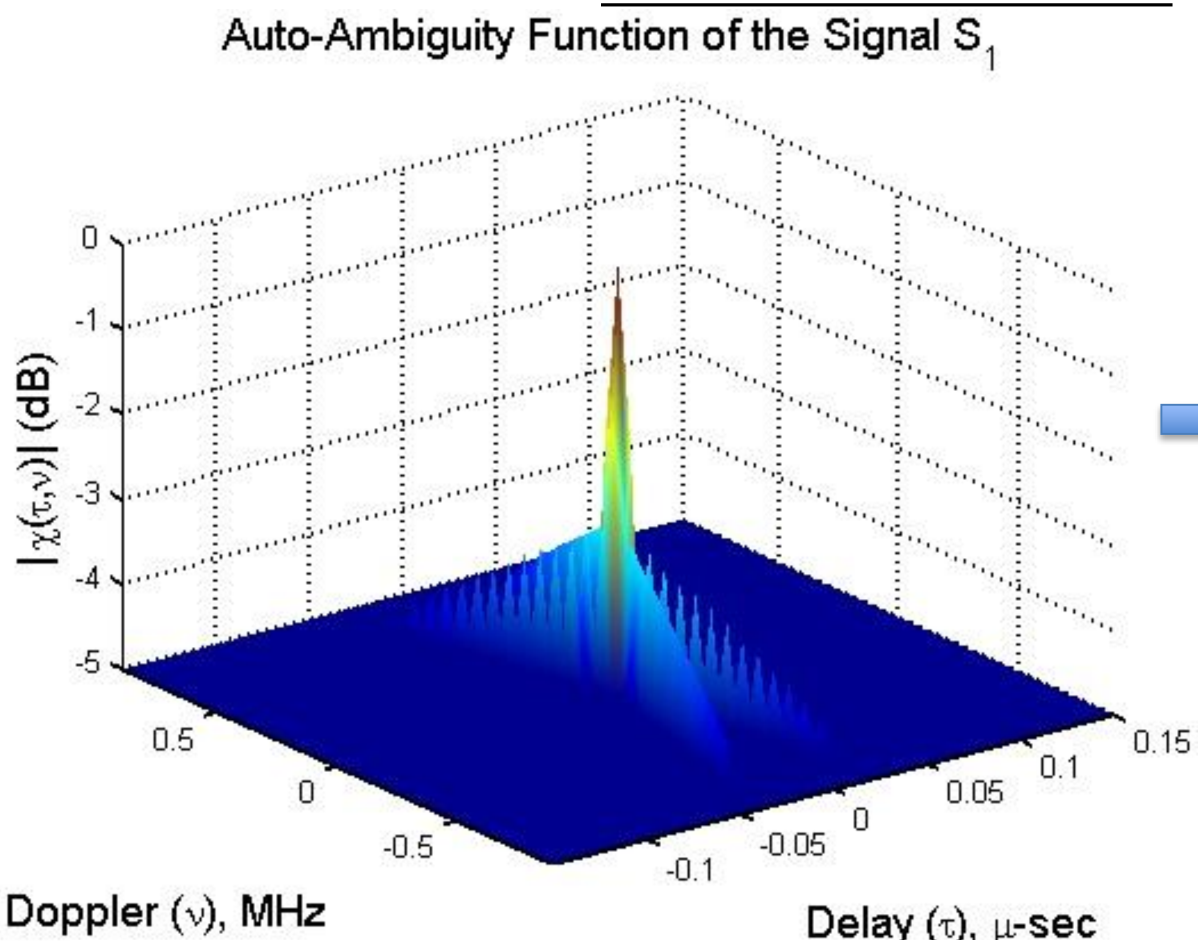
EXPERIMENT



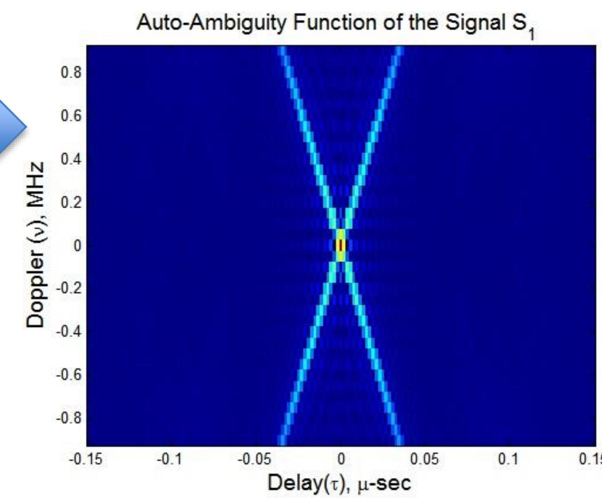
Spread spectrum coded LFM signal s_2 and corresponding Fourier transform. Chirp rates used were, $\alpha_1 = (2 * B)/TP_2$ and $\alpha_2 = (-2 * B)/TP_2$, where B is the bandwidth of the LFM signal after applying spread spectrum code, TP_2 is duration of the signal. Walsh-Hadamard code of length 64 has been used to spread the LFM signal.

ORTHOGONAL WAVEFORM DESIGN

RESULTS AND ANALYSIS

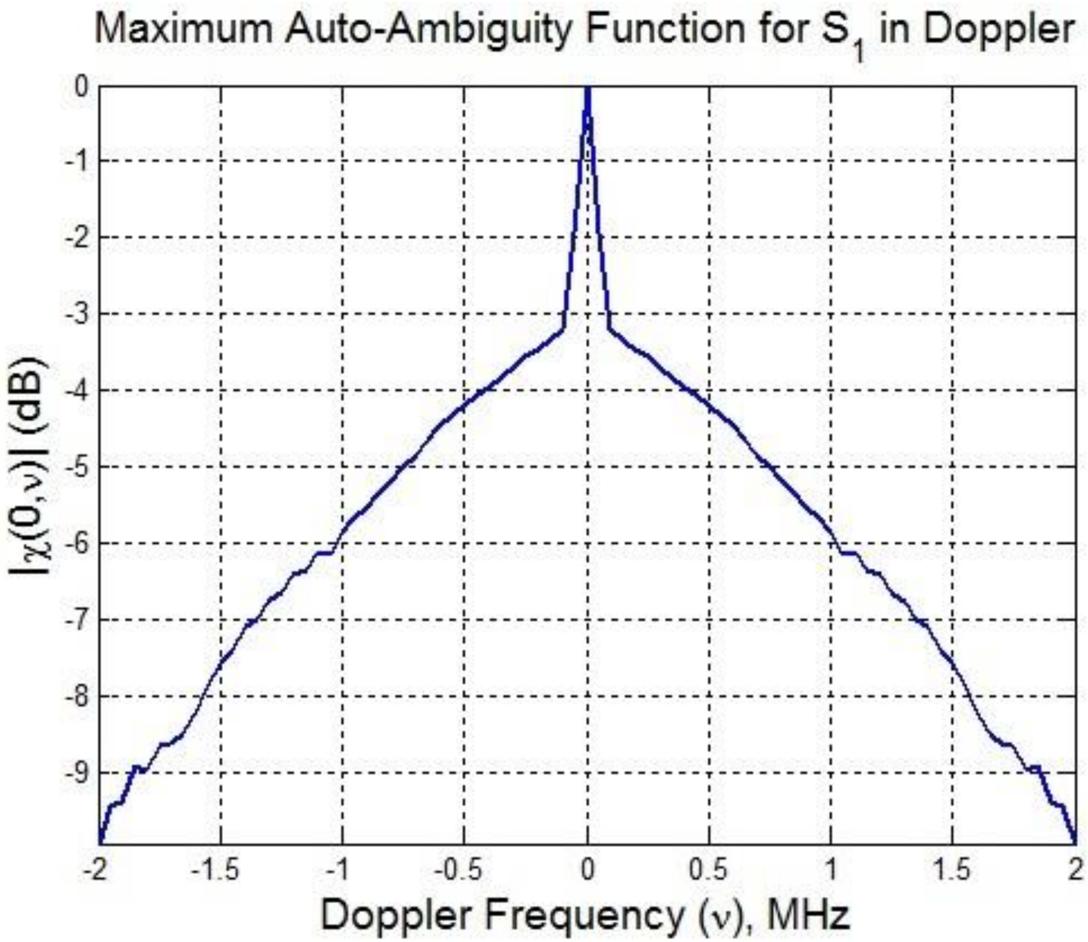


2D



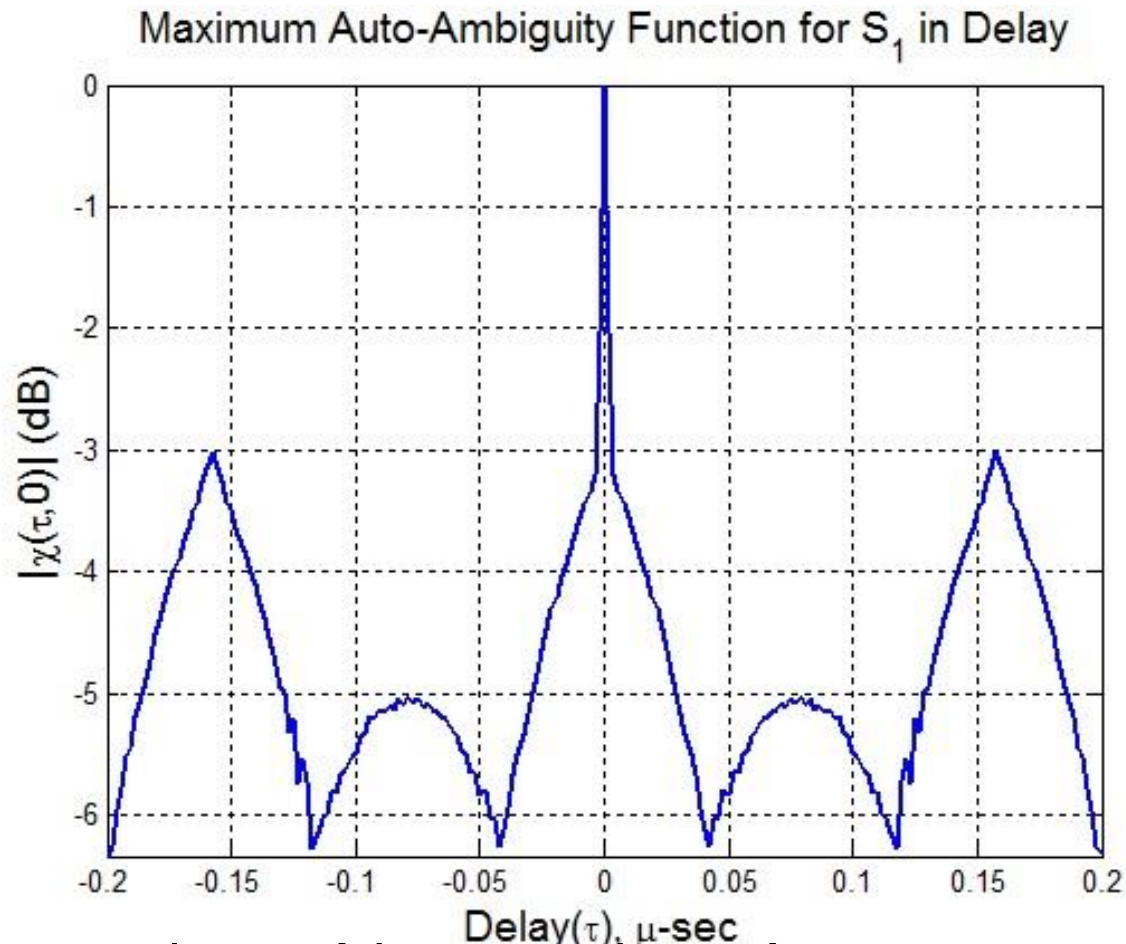
Auto-ambiguity function (AAF) of the LFM signal s_1. First, we generated s_1 using an up-chirp rate, $\alpha_1 = (1*B)/TP_1$ and down-chirp rate, $\alpha_2 = (-1*B)/TP_1$. Then this signal was spreaded with Walsh-Hadamard code of length 64. The AAF has been evaluated on the spreaded signal.

RESULTS AND ANALYSIS



Zero-delay cut of the auto-ambiguity function. Maximum auto-ambiguity in Doppler reaches to 0 dB.

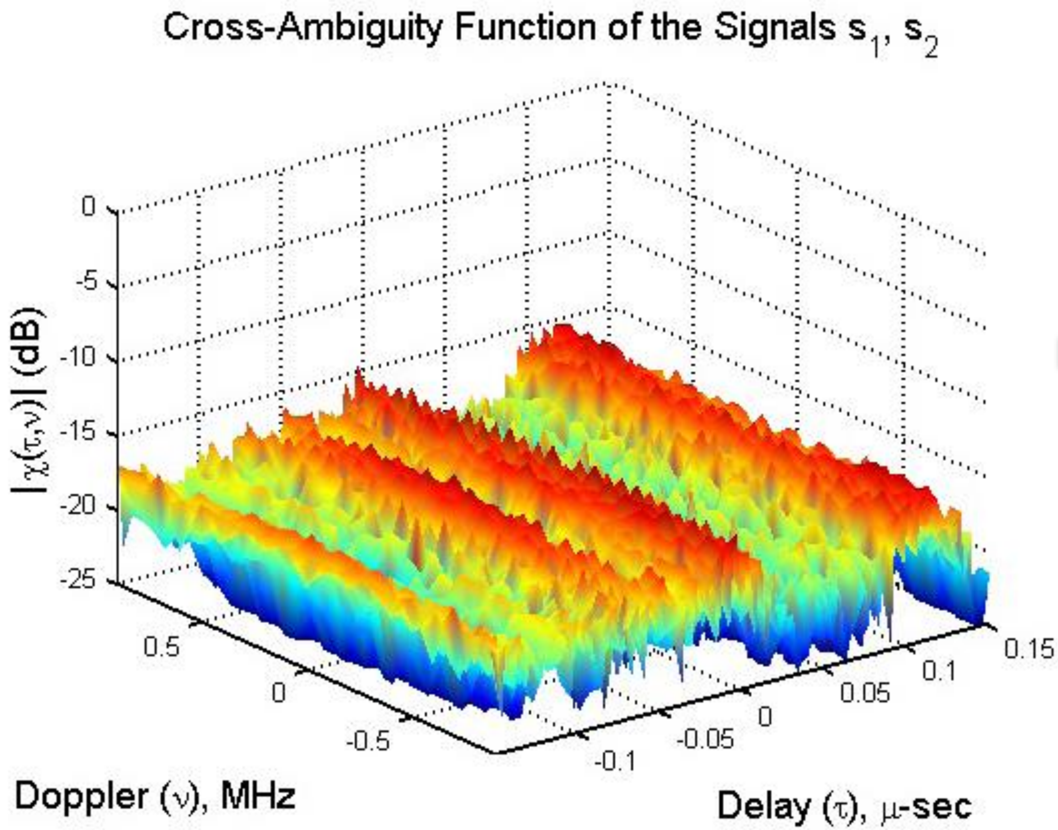
RESULTS AND ANALYSIS



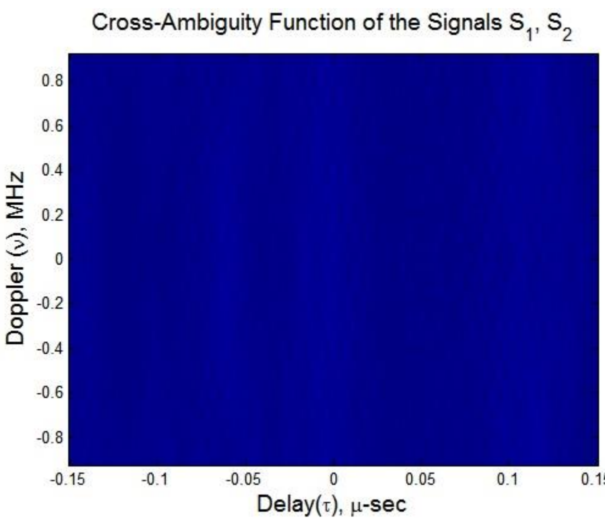
Zero-Doppler cut of the auto-ambiguity function. Maximum auto-ambiguity in delay reaches to 0 dB.

ORTHOGONAL WAVEFORM DESIGN

RESULTS AND ANALYSIS



2D



Cross-ambiguity function (CAF) of two LFM signals s_1 and s_2. First, we generated s_1 using an up-chirp rate, $\alpha_1 = (1 * B)/TP_1$ and down-chirp rate, $\alpha_2 = (-1 * B)/TP_1$. Second, we generated s_2 using an up-chirp rate, $\alpha_1 = (2 * B)/TP_1$ and down-chirp rate, $\alpha_2 = (-2 * B)/TP_1$. Then this signals were spreaded with Walsh-Hadamard code of length 64.

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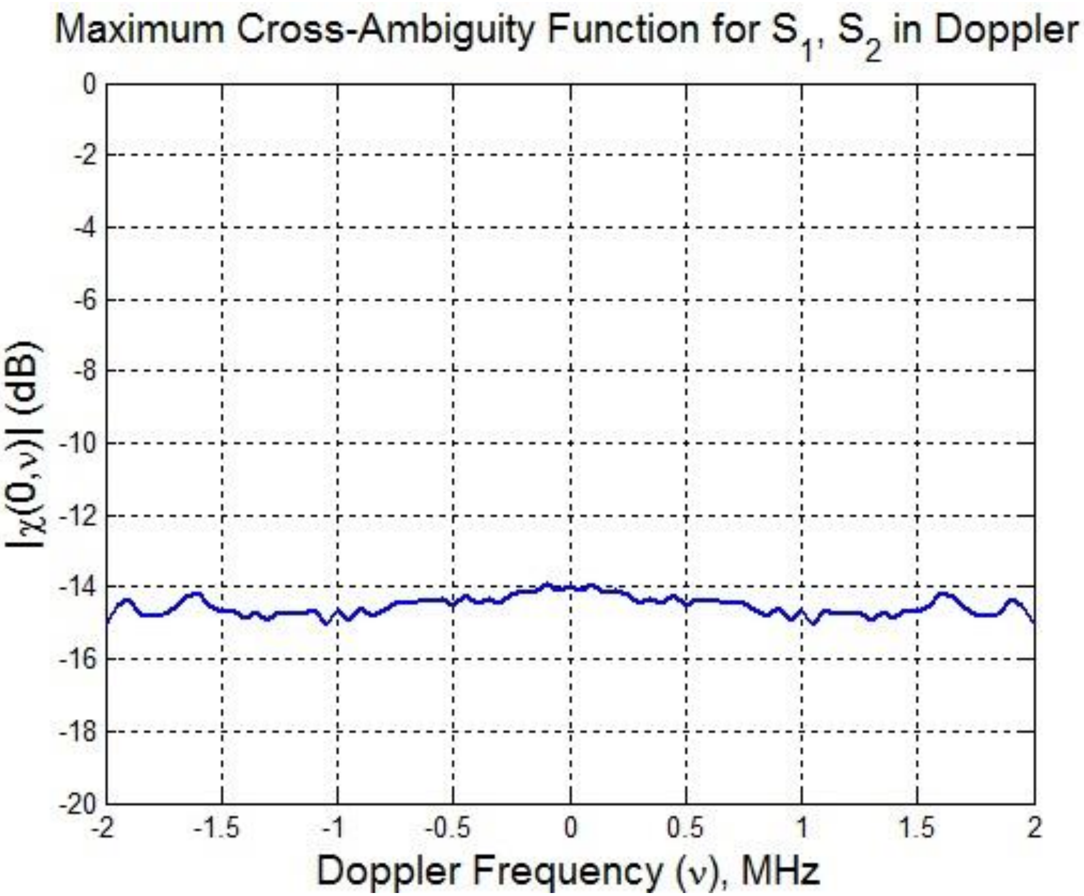
ORTHOGONAL WAVEFORM DESIGN

RESULTS AND ANALYSIS



Zero-delay cut of the cross-ambiguity function. Maximum cross-ambiguity in Doppler reaches to about -14 dB.

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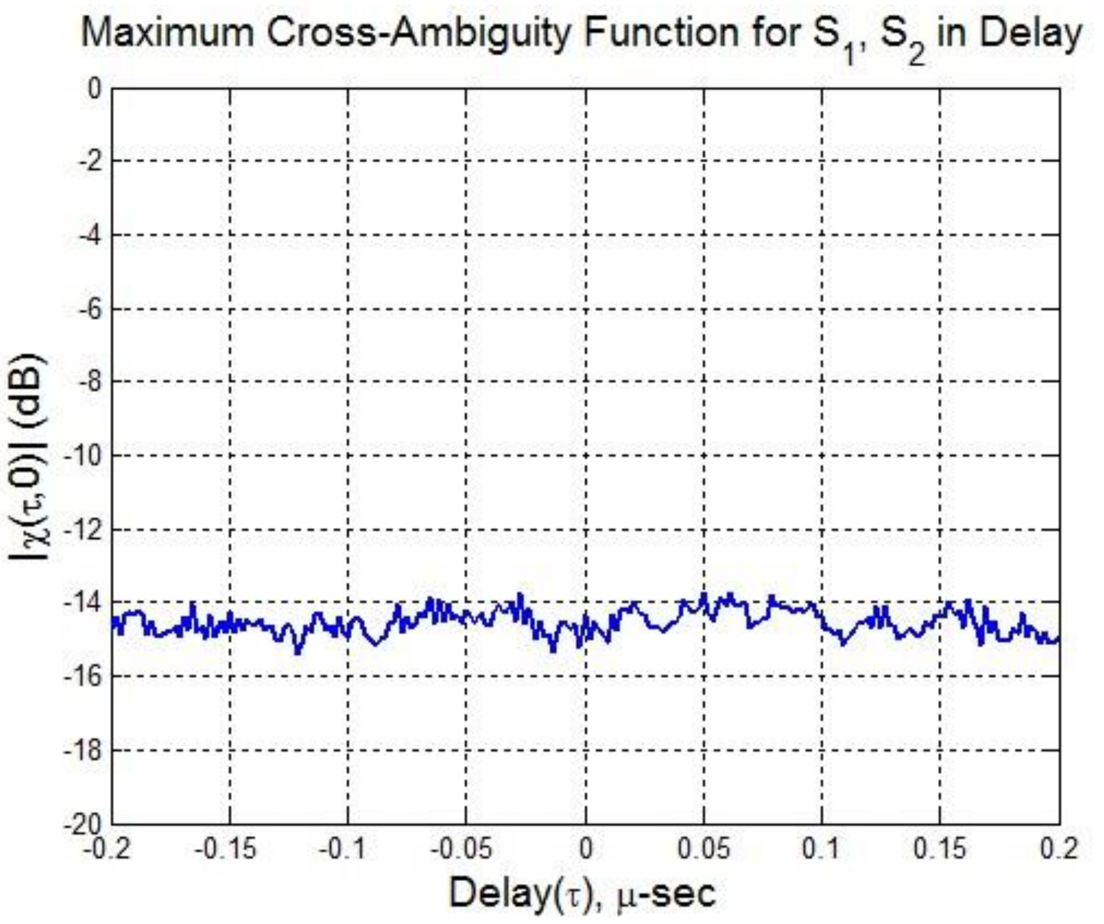
ORTHOGONAL WAVEFORM DESIGN

RESULTS AND ANALYSIS



Zero-Doppler cut of the cross-ambiguity function. Maximum cross-ambiguity in delay reaches to about -14 dB.

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RESULTS AND ANALYSIS (SUMMARY)

Code Type	Code Length	Bandwidth (MHz)	Max. AAF (dB)	Max. CAF (dB)
-	1	4	0	-5
Walsh-Hadamard	8	36	0	-9
Walsh-Hadamard	64	260	0	-14
Walsh-Hadamard	256	1000	0	-16
Biorthogonal	32	130	0	-13.5

SSCL Signaling Comparative Performance Analysis

SUMMARY

- ✓ We have designed a waveform combining LFM with spread spectrum coding technique.
- ✓ Simulated results from mathematical expression demonstrate effectiveness of this waveform to remain near orthogonal on receive
  - – We have seen that cross-ambiguity response (energy level) is very low compare to auto-ambiguity response
  - – Hence, we can separate each of the receive signal to matched filter it to the corresponding transmitted signal

PRESENTATION OUTLINE

- ✓ Research Problem
- ✓ Significance of this Research
- ✓ A Brief Overview on MIMO Radar/Waveform-agile Radar
- ✓ A Review on Radar Ambiguity Function, Orthogonal Waveform, Target Resolution and Doppler Tolerance
- ✓ Nearly Orthogonal Transmit and Receive Waveforms Design

► **Advanced Processing Capability of our Proposed Waveforms**

- High Resolution Imaging
- Non-interfering measurement

- Joint SAR and GMTI Processing
- Conclusion
- Future Research

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HIGH RESOLUTION IMAGING

Definition, Literature, and Our Contribution

<u>Resolution:</u>

a. **Range Resolution:** ***Bandwidth***
b. **Cross-Range Resolution:** ***Length of Aperture***

I. August W. Rihaczek. "Principles of High-Resolution Radar" Artech House Radar Library, 1996
II. N. Levanon and E. Mozeson, Radar Signals. Harlow, England: Wiley-IEEE Press, 1st ed., 2004.
III. 3. M. Soumekh, Fourier Array Imaging. New Jersey, NJ: Prentice-Hall, Inc, 1st ed., 1994.

<u>Our Unique Contribution:</u>

1. Processing the same received signal two different way
   - High Resolution (Combination of LFM + Coding Bandwidth),
   - LFM Resolution, after despreading
2. Non-interfering measurement to obtain V-Chirp Resolution and Doppler Tolerant concurrently

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HIGH RESOLUTION IMAGING

- Usually individual transmit waveforms are designed with fixed bandwidth. For this reason, resolution of these waveforms are also fixed.
- Our waveforms are designed by combining LFM signals and spread spectrum coding. So, our waveforms contain an LFM signal's bandwidth as well as bandwidth expansion due to spread spectrum coding.
- As a result, if we process our received waveforms using matched filtering of the spreaded high bandwidth signal, we get extra bandwidth for finer resolution.
- By contrast, if we process our received waveforms after despreading using matched filtering of the resulting LFM signals, we only get the baseline LFM waveforms bandwidth and resolution capability

HIGH RESOLUTION IMAGING

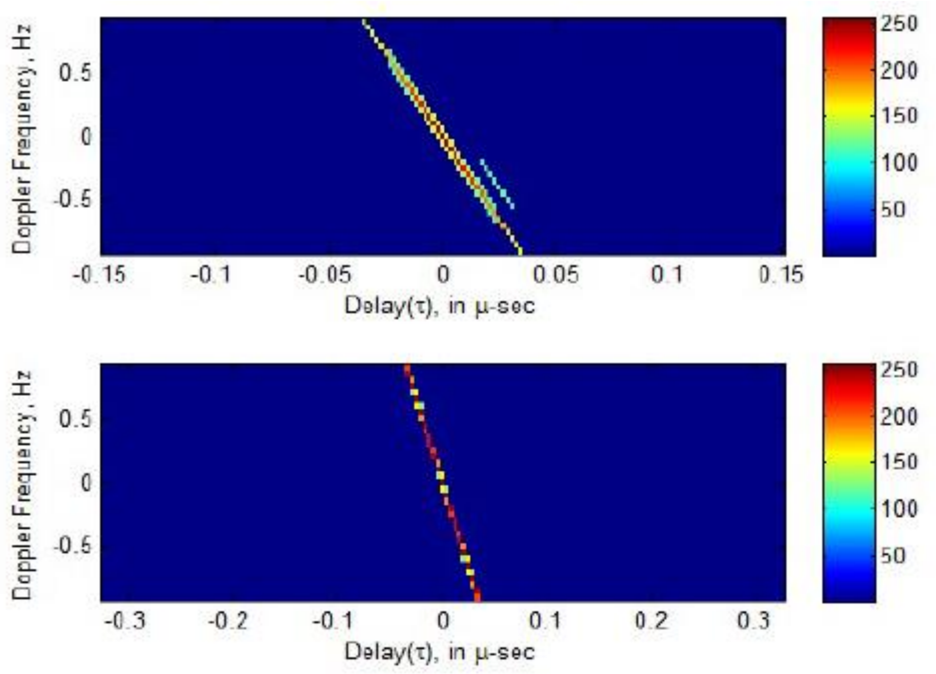

Fig. Images of two point targets with a single chirp; strong target is located at the center (0,0) of delay-Doppler plane; the weak target is located at slightly off center. The top image demonstrates that processing the received signals with spread spectrum code on it, we can detect both targets. The bottom image demonstrates that without spread spectrum code, we cannot detect the weak target.

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HIGH RESOLUTION IMAGING

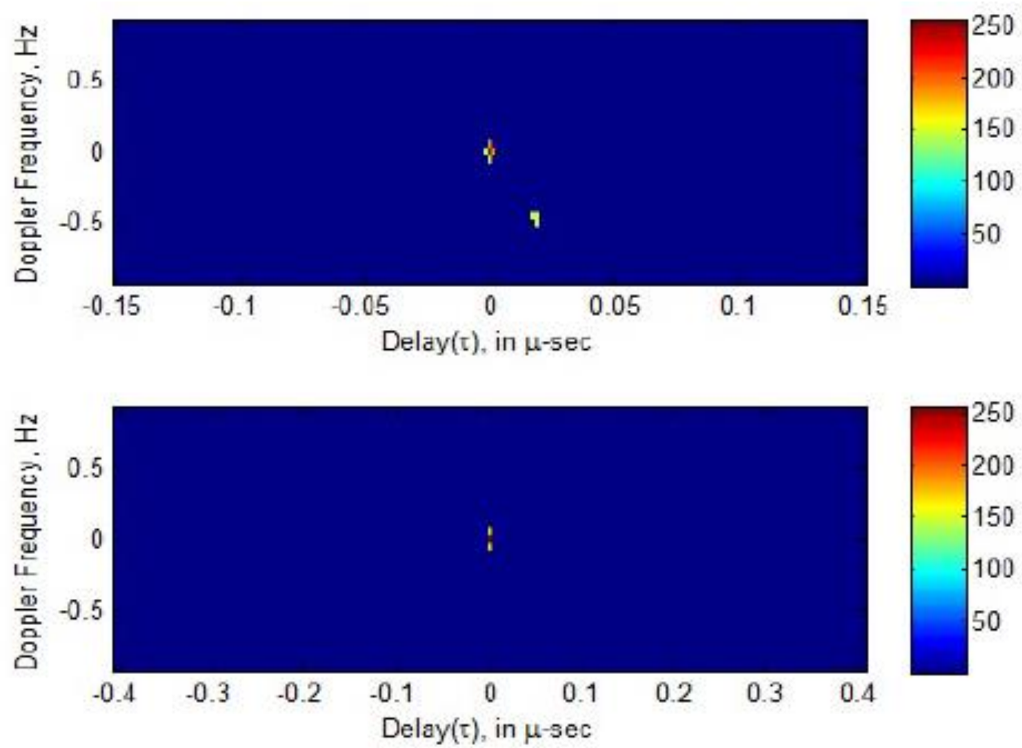

Fig. 4.2. Images of two point targets with two chirps; strong target is located at the center (0,0) of delay-Doppler plane; the weak target is located at slightly off center. The top image demonstrates that processing the received signals with spread spectrum code on it, we can detect both targets. The bottom image demonstrates that without spread spectrum code, we cannot detect the weak target.

NON-INTERFERING, WAVEFORM DIVERSE MEASUREMENTS

- Because of orthogonal coding, we can get non-interfering measurements by our proposed waveforms. This could be useful "V-Chirp" Signaling

- A "V-chirp" can be useful for improving target resolution. However, traditional approach for generating "V-Chirp" also reduces Doppler Tolerance

- When we matched filter two despreaded LFM signals (one could be an up-chirp signal and the other could be a down-chirp signal) with their respective matched filters, it is as if we get two simultaneous non-interfering measurements with each of the LFM signals. This approach provides improved target resolution without sacrificing Doppler Tolerance

NON-INTERFERING, WAVEFORM DIVERSE MEASUREMENTS

- When radar system is capable of operating multiple waveforms using several independent channels without any interference, output of each channel has a two-dimensional image of the target environment

For a point target located at $(\tau_0,\, \upsilon_0)$,

this can be formulated as

$$
\begin{aligned}
\mathrm{O}_T^0(\tau,\upsilon) &= e^{i\phi} e^{-i2\pi(\upsilon-\upsilon_0)\tau_0} \chi_{s0}(\tau-\tau_0,\upsilon-\upsilon_0) \\
&= \tilde{\chi}_{s0}(\tau-\tau_0,\upsilon-\upsilon_0) \\
\mathrm{O}_T^1(\tau,\upsilon) &= e^{i\phi} e^{-i2\pi(\upsilon-\upsilon_0)\tau_0} \chi_{s1}(\tau-\tau_0,\upsilon-\upsilon_0) \\
&= \tilde{\chi}_{s_1}(\tau-\tau_0,\upsilon-\upsilon_0) \\
&\vdots \quad \vdots \\
\mathrm{O}_T^{N-1}(\tau,\upsilon) &= e^{i\phi} e^{-i2\pi(\upsilon-\upsilon_0)\tau_0} \chi_{s_0}(\tau-\tau_0,\upsilon-\upsilon_0) \\
&= \tilde{\chi}_{s_{N-1}}(\tau-\tau_0,\upsilon-\upsilon_0)
\end{aligned}
$$

NON-INTERFERING, WAVEFORM DIVERSE MEASUREMENTS

where $\mathrm{O}_T^i(\tau, \upsilon)$ is the image obtained through the i-th channel and $\tilde{\chi}$ denotes complex modulation factor $e^{i\phi}e^{-i2\pi(\upsilon-\upsilon_0)\tau_0}$. By coherently summing the images up, we get the composite image,

$$\mathrm{O}_T^C(\tau, \upsilon) = e^{i\phi}e^{-i2\pi(\upsilon-\upsilon_0)\tau_0} \sum_{i=0}^{N-1} \chi_{s_i}(\tau - \tau_0, \upsilon - \upsilon_0).$$

The above expression can be thought of as an image of a point target generated by a new point-spread function

$$C(\tau, \upsilon) = \sum_{i=0}^{N-1} \chi_{s_i}(\tau, \upsilon)$$

This new point-spread function is known as *Composite Ambiguity Function (CAF)* or *Combined Ambiguity Function* .

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NON-INTERFERING MEASUREMENTS FOR BETTER TARGET RESOLUTION

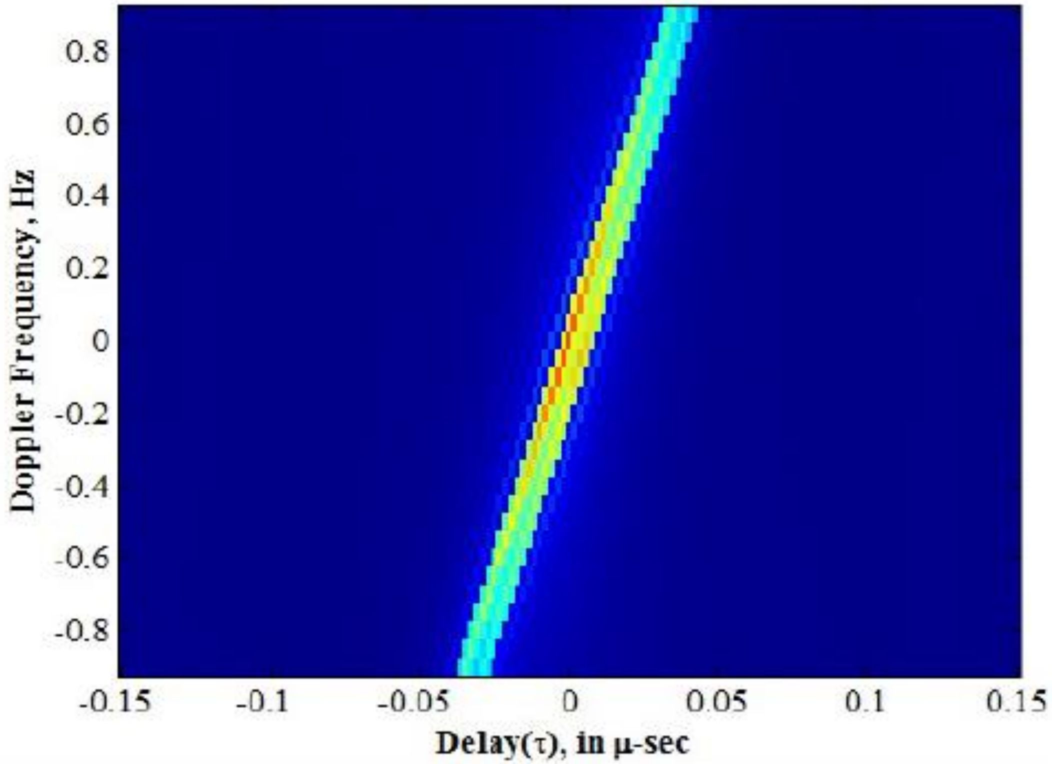

Fig. Two targets are closely-spaced in the image scene. Measurement with a single chirp could be difficult to resolve these targets

NON-INTERFERING MEASUREMENTS FOR ENHANCED TARGET RESOLUTION

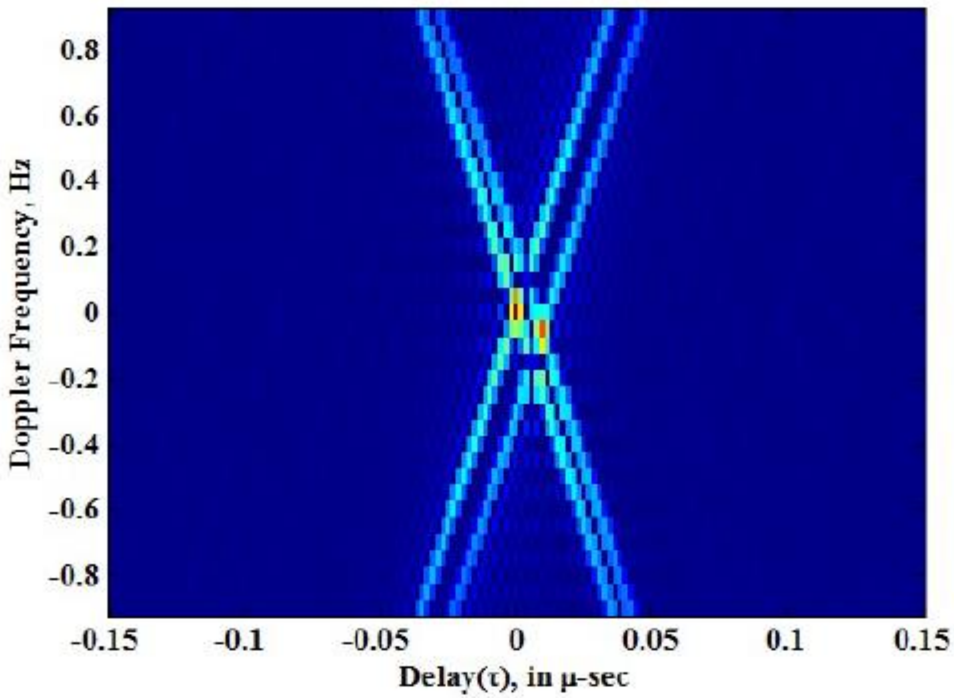

Fig. Two targets are closely-spaced in the image scene. By using two waveforms we can resolve these targets. First we make a measuremnet with a coded up-chirp waveform, then with a coded down-chirp waveform. After despreading operation at the receiver, we coherently combine these two waveform. This provides independent look of the point scatterers by two different waveforms, thus better delay-Doppler resolution

HIGH RESOLUTION IMAGING

SUMMARY

- ✓ We have shown that coding enables additional bandwidth

  (Baseline LFM Bandwidth + Spectrum Coding)

  - In some applications, we can exploit this capability to resolve targets

- ✓ We can perform non-interfering measurement to obtain desired resolution and preserve the Doppler Tolerant capability

PRESENTATION OUTLINE

- ✓ Research Problem
- ✓ Significance of this Research
- ✓ A Brief Overview on MIMO Radar/Waveform-agile Radar
- ✓ A Review on Radar Ambiguity Function, Orthogonal Waveform, Target Resolution and Doppler Tolerance
- ✓ Nearly Orthogonal Transmit and Receive Waveforms Design
- ✓ High Resolution Imaging / Advanced Processing Capability of our Proposed Waveforms
- ► Joint SAR and GMTI Processing
  - **Problem Statement**
  - **Terminology**
  - **Research Objectives**
  - **Previous Research**
  - **Proposed Technical Solution**
  - **Orthogonal Waveform Research**
  - **SAR and Endoclutter GMTI and SAR Processing**
  - **Exoclutter GMTI Processing**
  - **Moving Target Focusing**
- Conclusion

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PROBLEM STATEMENT

- **Radar systems are configured to operate either in GMTI or SAR processing mode:**

  <u>Requirements for these two modes are different</u>

  1. **Exoclutter (fast moving target detection) GMTI requires a high PRF rate**
     - **A high PRF results in increased range ambiguity and processing burden in SAR imaging**
  2. **SAR Imaging and Endoclutter (slow moving target detection) GMTI requires a low PRF rate**
  3. **Exoclutter GMTI pulses don't require high bandwidth; however, SAR pulses require high bandwidth**

A Solution to this problem will result in Rapid Target Recognition and reduce cost for Radar System operations

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Exoclutter and Endoclutter

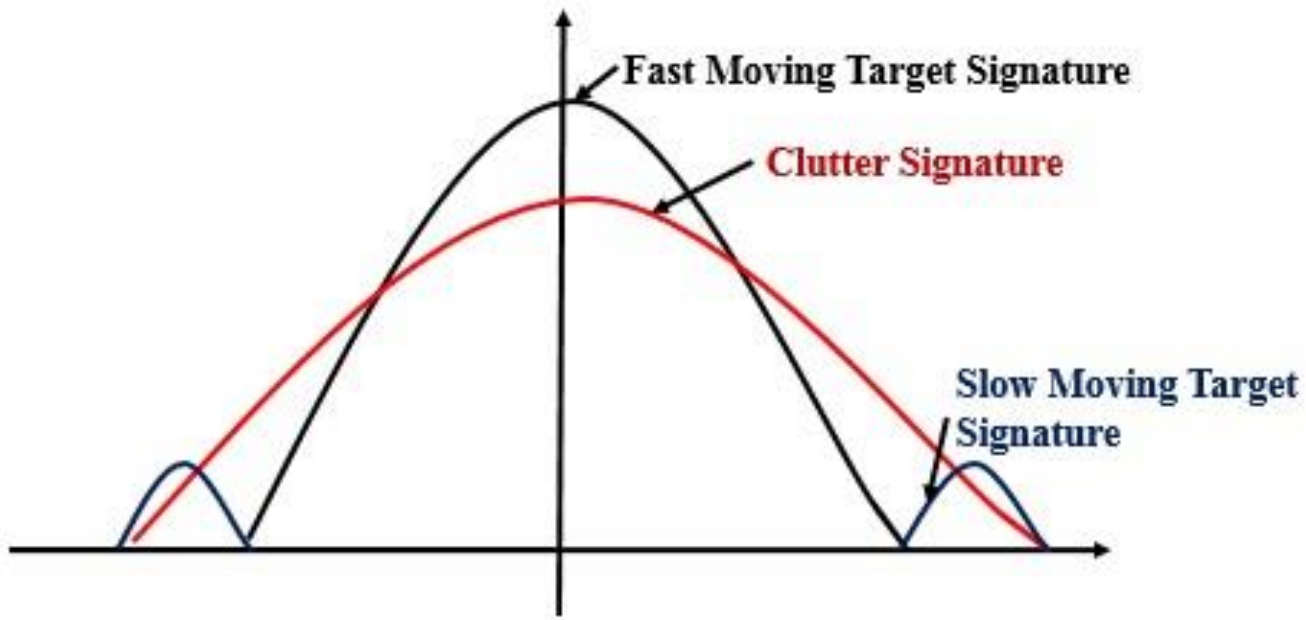
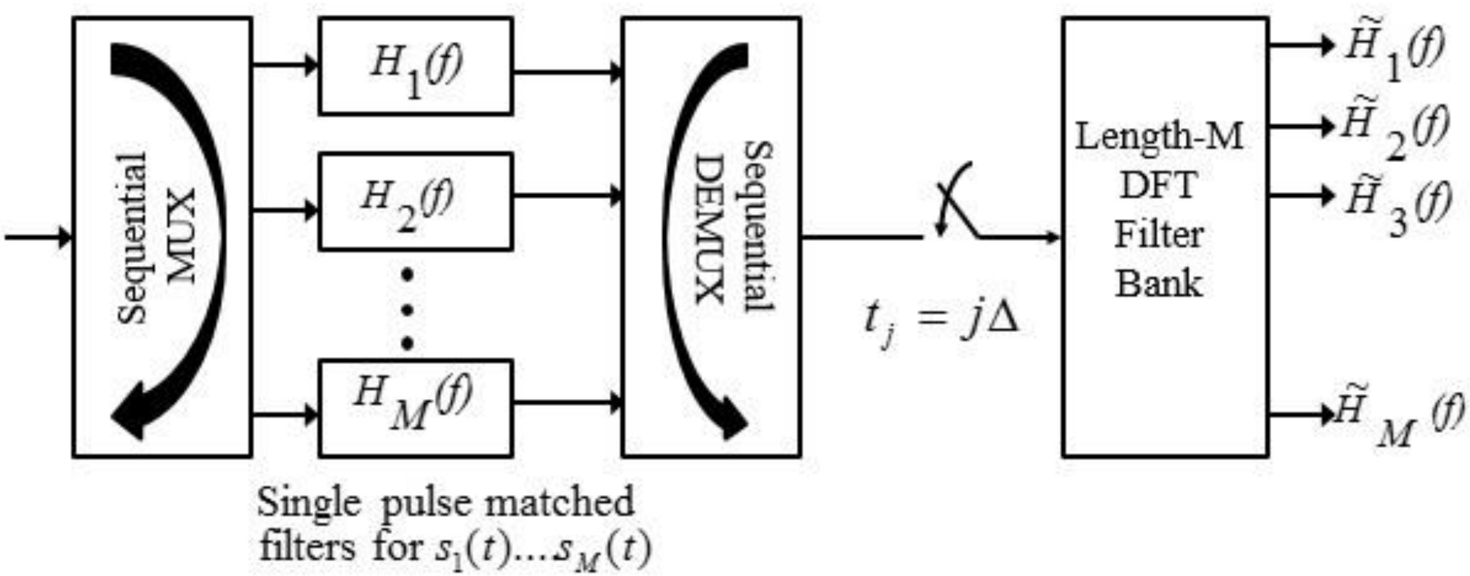


Fig. Spectrum of fast moving target, clutter, and slow moving target.

Exoclutter GMTI / Fast Moving Target Detection
Endoclutter GMTI / Slow Moving Target Detection

Multiplexed Waveform Pulse-Doppler Processor (MWPDP)



M.R.Bell and S.Monrocq., Diversity waveform signal processing for delay-Doppler measurement and imaging," Digital Signal Processing, vol. 12, no. 2, 2002.

OUR RESEARCH OBJECTIVES

- **Accomplish GMTI and SAR processing concurrently by eliminating the complexities associated with reconfiguring a radar system**
- **Use appropriate PRFs for GMTI processing and SAR imaging**
- **Efficient BW utilization by employing appropriate BW for Exoclutter GMTI pulses and SAR image formation pulses**

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PREVIOUS RESEARCH ON JOINT GMTI AND SAR PROCESSING

- **Davis presented common waveforms for simultaneous SAR and GMTI processing**
- **Murthy, Pillai, and Davis also presented Frequency-jump burst waveforms**

The main idea for above approach is that extract some portion of the waveforms for SAR and other portion for GMTI

Unlike the above methods, our method utilizes orthogonality of Tx and Rx waveforms to accomplish GMTI and SAR processing concurrently

M. Davis, R. Kapfer and R. Bozek, Common Waveform for Simultaneous SAR and GMTI, Proceedings of IEEE Radar Conference 2011, Kansas City, MO, USA.

V. Murthy, U. Pillai and M. Davis, Waveforms for Simultaneous SAR and GMTI, Proceedings of IEEE Radar Conference 2012, Atlanta, Georgia, USA.

PROPOSED TECHNICAL SOLUTION FOR JOINT GMTI AND SAR

- **Transmit a group of orthogonal pulses/signals (e.g. 11 pulses) at a time and repeat**
  - **Among these pulses, first pulse is designated as SAR pulse and coded with *C*; the remaining pulses are designated as GMTI pulses and coded with *D***
  - **At the receiver, codes will be used to separate GMTI pulses from the SAR pulse**

PROPOSED TECHNICAL SOLUTION

- **SAR pulse is designed to provide high bandwidth (e.g. 600 MHz) for SAR imaging and for coherent change detection for endoclutter (slow moving target detection) GMTI processing**
  - **The PRF rate for SAR pulses will be low (e.g. 300Hz)**

- **Exoclutter GMTI pulses are designed with a low bandwidth (e.g. 200 MHz)**
  - **The PRF rate is set to high (e.g. 1500Hz) to resolve Doppler ambiguity**

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ORTHOGONAL WAVEFORMS FOR OUR RESEARCH

-Spread Spectrum Coded Linear Frequency Modulated (LFM) Orthogonal Waveforms have been proposed for this research

- Other orthogonal waveforms can be used as well

$$s_1(t) = \sum_{m}^{M-1} C_m P(t - mT_C).e^{i\pi\alpha_1 t^2}$$

$$s_2(t) = \sum_{n}^{N-1} D_n P(t - nT_C).e^{i\pi\alpha_2 t^2}$$

where

C_m : *First Code Sequence*

D_n : *Second Code Sequence* (*different from* C_m)

T_C : *Chip Time*

α_1, α_2 : *Different Chirp Rates*

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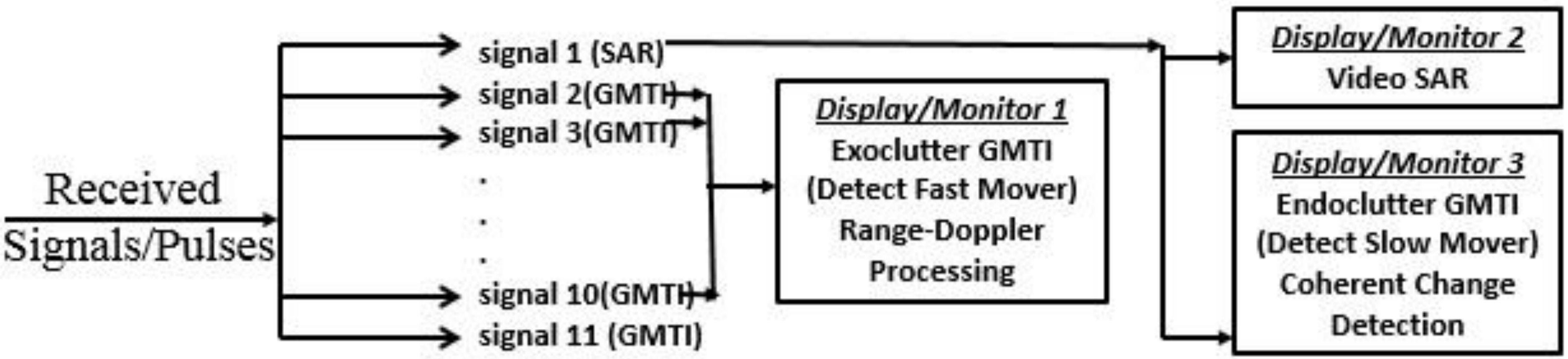
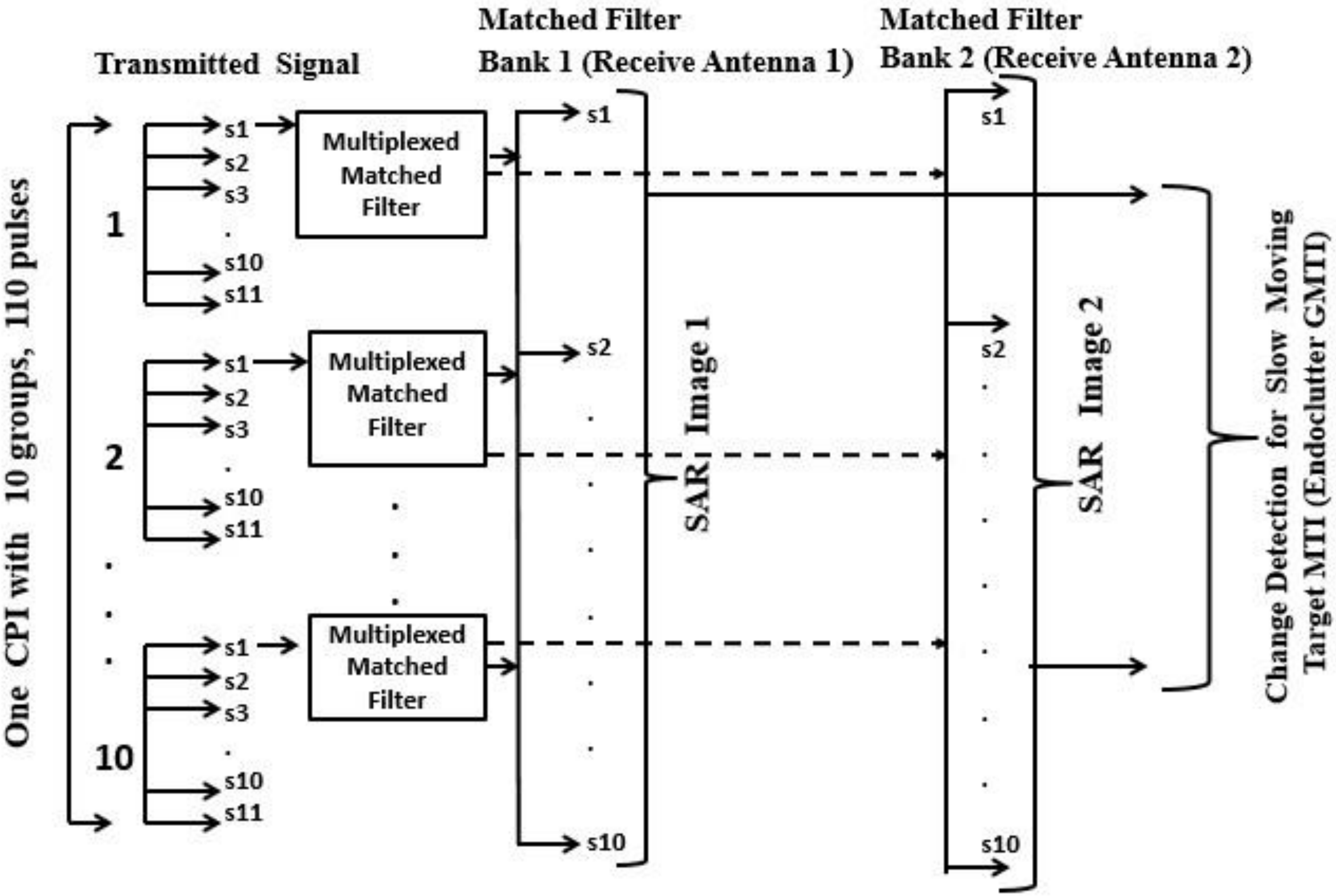
BLOCK DIAGRAM FOR JOINT GMTI AND SAR PROCESSING

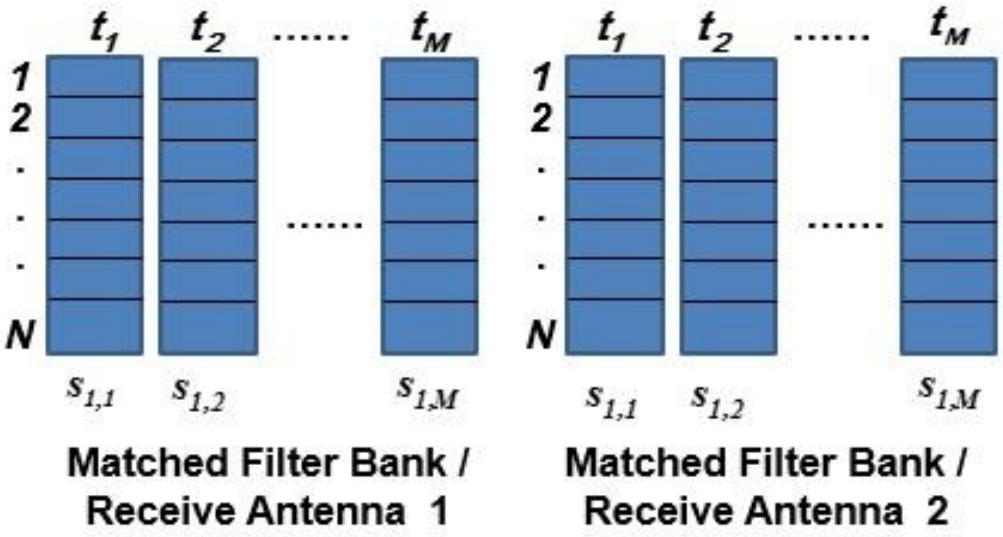


Joint GMTI and SAR processing concept. We will transmit a group of 11 pulses at a time and repeat. Transmit pulse 1 is SAR pulse and coded with C. This waveform provides bandwidth of 600 MHz for high resolution SAR images and coherent change detection for endoclutter GMTI (to detect slow movers). PRF rate for SAR pulse is 300Hz. Transmit pulses 2-11 are exoclutter GMTI pulses and coded with D. These waveforms provide bandwidth of 200 MHz and PRF for these pulses is 1500Hz to detect the fast movers using Doppler

ENDOCLUTTER GMTI AND SAR PROCESSING



ENDOCLUTTER GMTI AND SAR PROCESSING



Phase history data recording for endoclutter GMTI algorithm and SAR processing. $s_{1,1}$ is pulse 1 (SAR pulse) at time t_1; similarly, $s_{1,M}$ is pulse 1 at time t_M. We will perform DPCA based coherent change detection to detect the slow movers.

Parameters	Value
PRF	300
Bandwidth	600MHz
Radar Platform Velocity	75 m/sec
Carrier Frequency	16.9 GHz
Target Speed	5 m/sec

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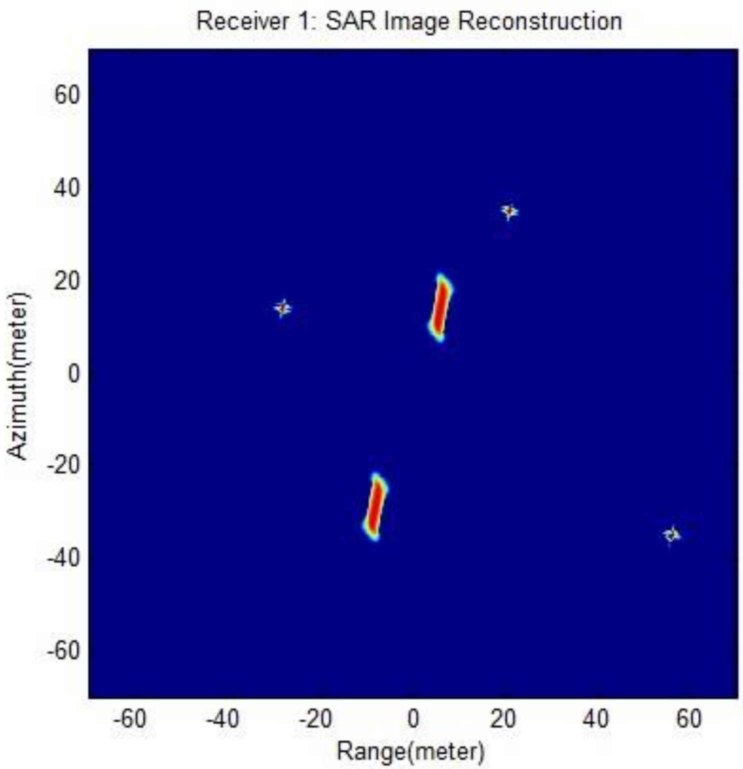
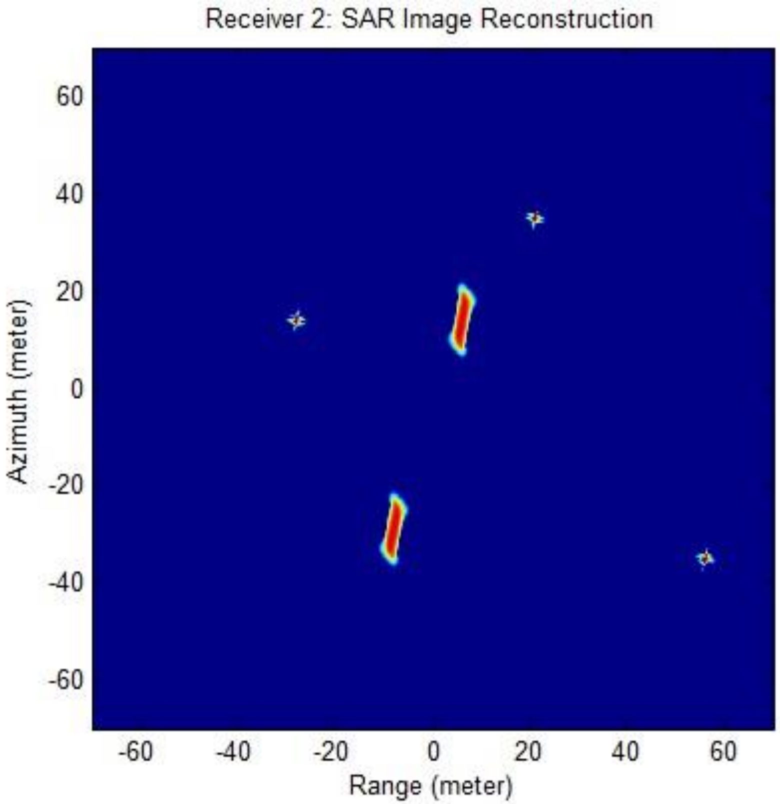
RESULTS: ENDOCLUTTER GMTI AND SAR PROCESSING





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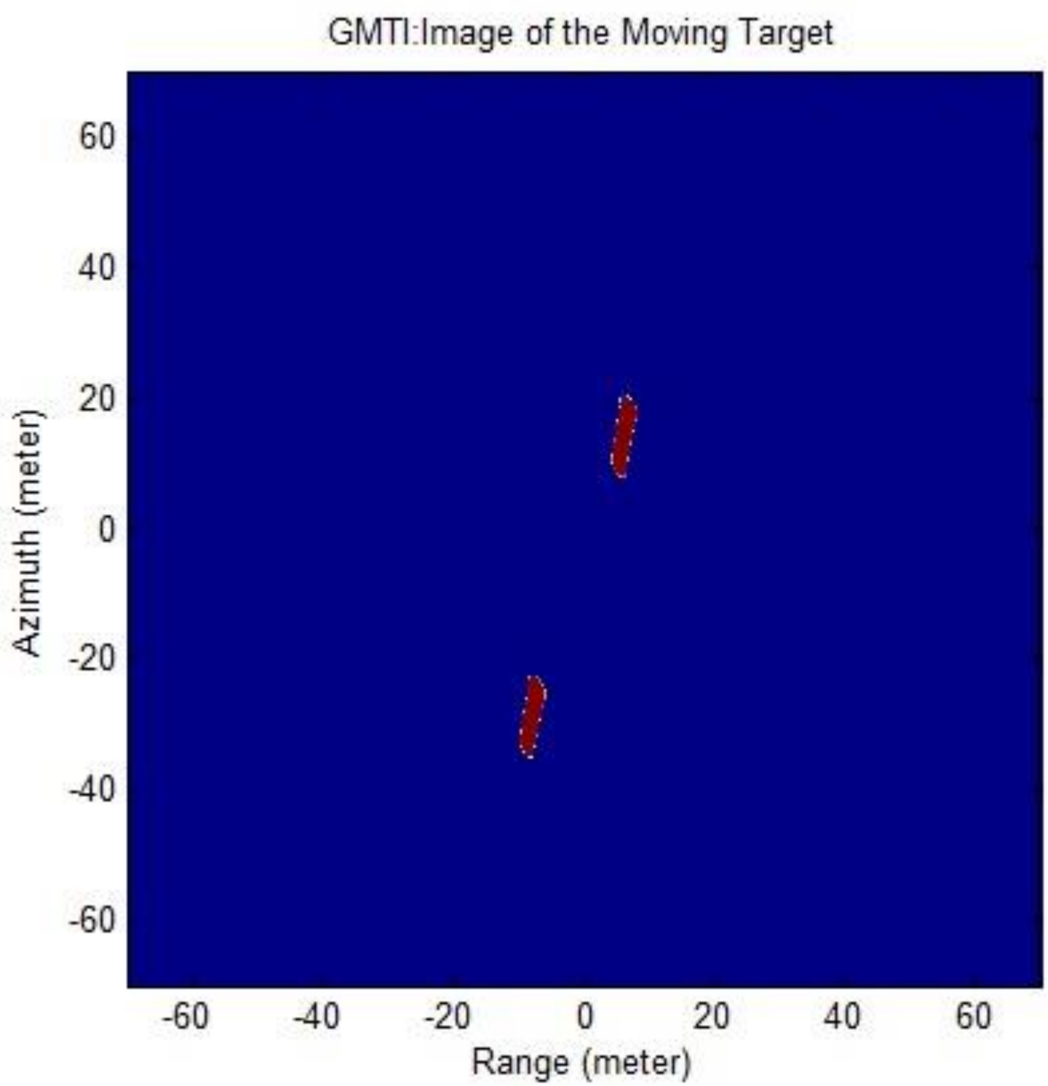
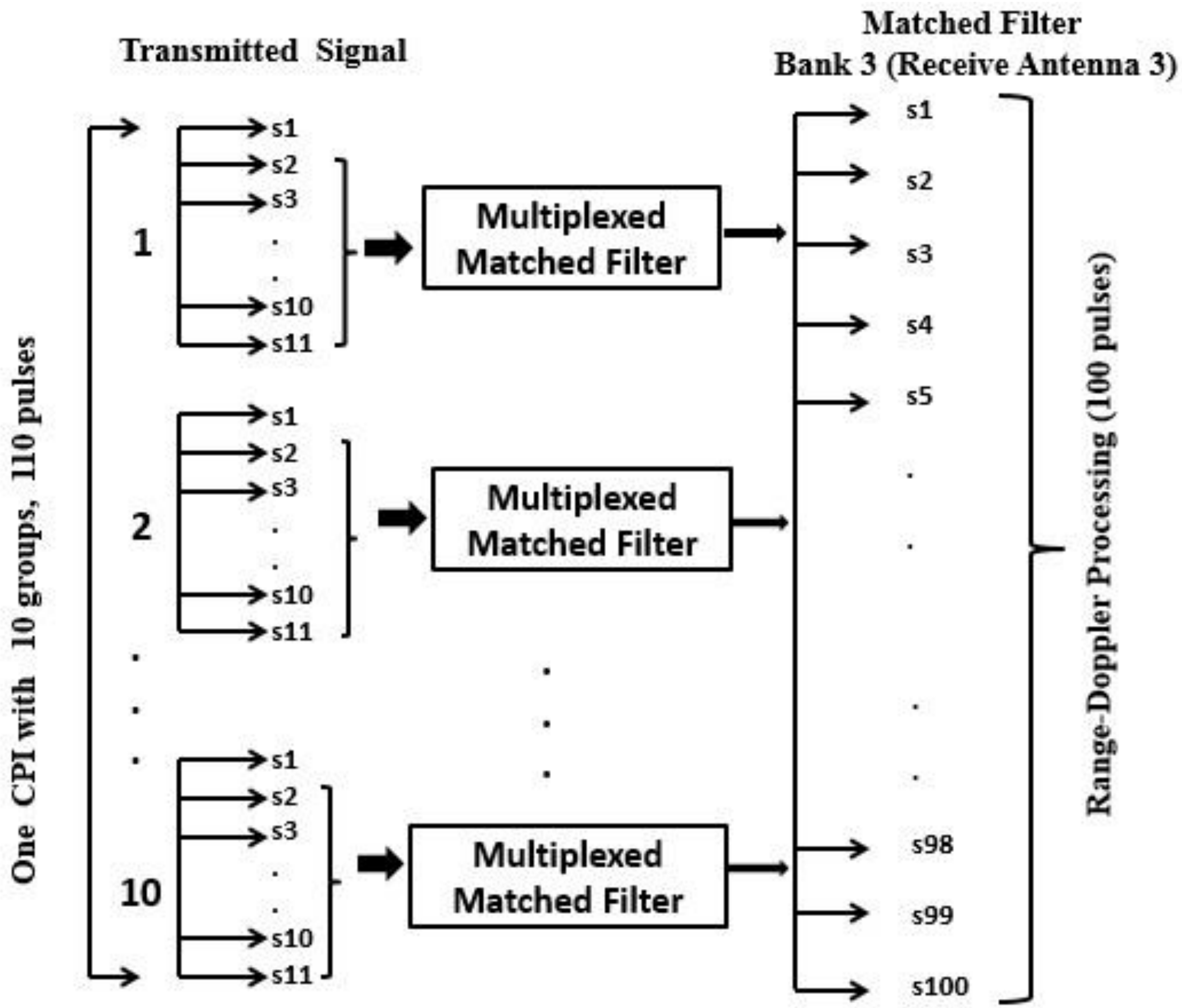
RESULTS: ENDOCLUTTER GMTI AND SAR PROCESSING

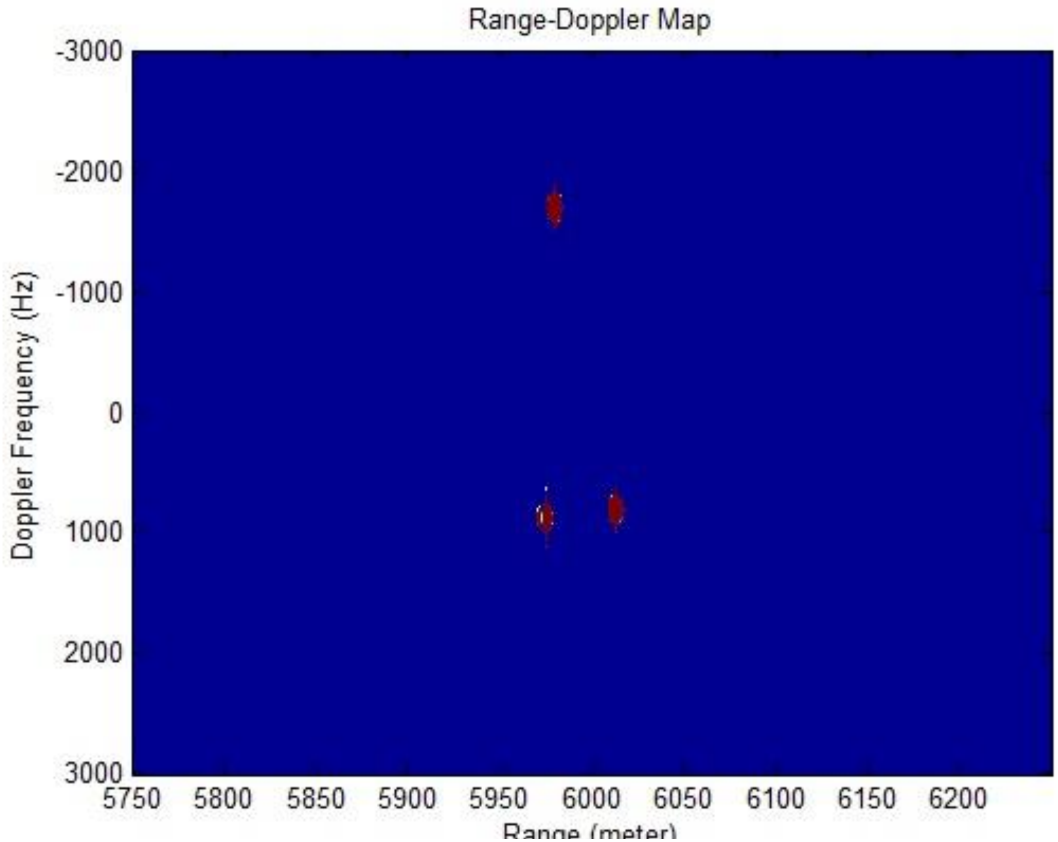


EXOCLUTTER GMTI PROCESSING



RESULTS: EXOCLUTTER GMTI PROCESSING

Parameters	Value
PRF	1500
Bandwidth	200MHz
Radar Platform Velocity	75 m/sec
Carrier Frequency	16.9 GHz



Range-Doppler processing to detect fast moving targets. The interrogated scene has three moving targets. Two targets have same velocity; hence they generated same Doppler frequency.

CONCLUSION: JOINT GMTI AND SAR PROCESSING

- ✓ We presented a signal processing framework for Joint GMTI and SAR Applications
  - ➢ Orthogonality of our waveforms allow separating SAR and GMTI signals at the receiver and hence process them separately

- ✓ Our approach accomplishes GMTI and SAR processing concurrently by eliminating the complexities associated with reconfiguring a radar system

- ✓ Our approach allows more efficient use of bandwidth by employing appropriate bandwidth for exoclutter GMTI pulses and SAR image formation pulses

- ✓ Our approach allows reducing range ambiguity issue associated with high PRF operation

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PRESENTATION OUTLINE

- ✓ Research Problem
- ✓ Significance of this Research
- ✓ A Brief Overview on MIMO Radar/Waveform-agile Radar
- ✓ A Review on Radar Ambiguity Function, Orthogonal Waveform, Target Resolution and Doppler Tolerance
- ✓ Nearly Orthogonal Transmit and Receive Waveforms Design
- ✓ Advanced Processing Capability of our Proposed Waveforms
- ✓ Joint SAR and GMTI Processing

► Conclusion

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CONCLUSION

1. **We defined approximate orthogonality, resolution, and Doppler tolerance of waveforms in a matched filter radar**

2. We Design Waveforms for Waveform-agile Radar Applications that Satisfy Following Specifications

- ✓ Orthogonal on Transmit and Nearly Orthogonal on Receive
- ✓ Exhibit Doppler Tolerant Property

3. Demonstrate Non-interfering Measurement Capabilities (for High Resolution Imaging) of these Waveforms

4. Develop A Signal Processing Framework for Joint GMTI and SAR Processing based on our Proposed Waveforms

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THANK YOU

MIMO VS. TRADITIONAL RADAR

I. MIMO Allows Processing Diversity Gains
- Can transmit orthogonal, diverse waveforms
- Receive orthogonal waveforms
- Can mitigate onerous challenges imposed by complex and contested environments

II. A New Paradigm for Radar Signal Processing
- Exploitation techniques surrounding “traditional radar concepts” reached to a limit
- “Opened the door” for new research to tackle detection of difficult/low RCS targets in composite environment while EM spectrum is also rapidly shrinking

III. Conventional Radars Experience Target Scattering Fluctuations of 5-25 dB
- When RCS fluctuates slowly, it causes fading and degrades radar performance
- MIMO radar exploits angular spread to increase radar performance

*** For MIMO, we will have less power density on transmit (No Beamforming on transmit)

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