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*Technology Serving Humanity*

## MEMORANDUM

Subject: Progress Report  
ULI: FY13 Q3 Progress Report (4/1/2013–6/30/2013)

This document provides a progress report on the project “Advanced Digital Signal Processing” covering the period of 4/1/2013–6/30/2013.

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*Revolutionary Research . . . Relevant Results*

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*defy convention*

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## Advanced Digital Signal Processing for Hybrid Lidar

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*Presented to:*

**Annual ULI program review attendees**

June 6, 2013

*Presented by:*

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# Outline



- Background and Objectives
- Approach and Challenges
- Light Propagation in Water
- Progress
  - New ranging technique
  - New backscatter reduction technique
- Summary

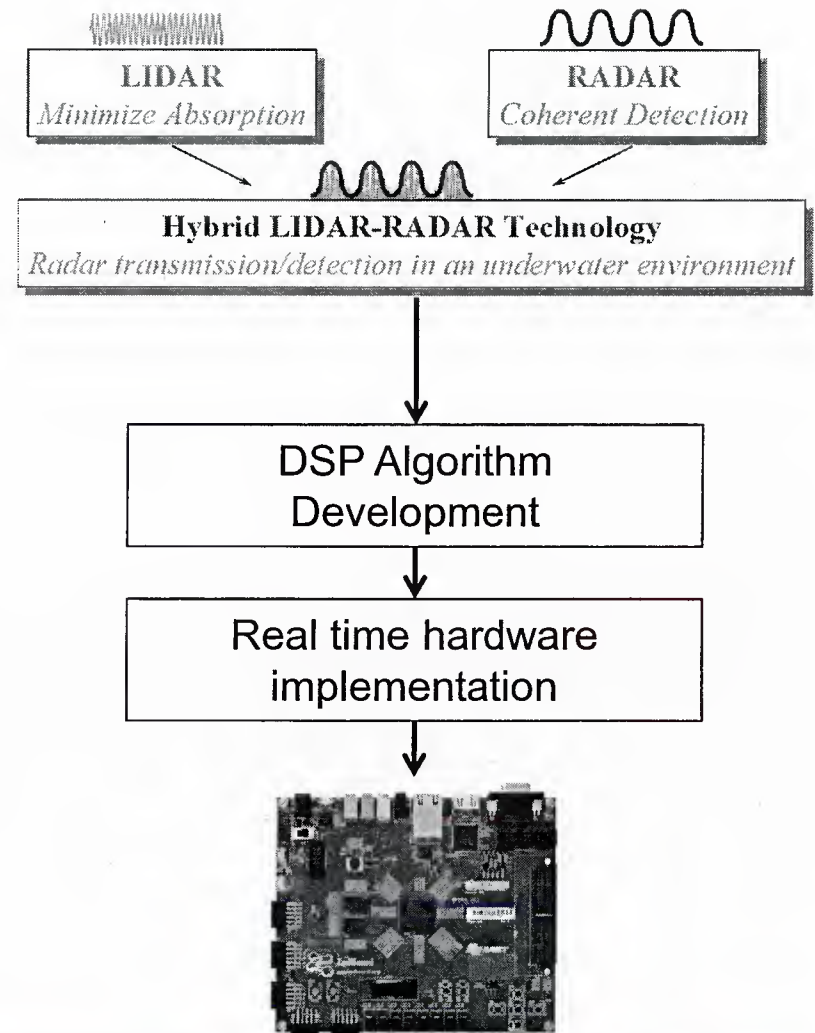


**Background:** The Navy uses hybrid lidar-radar for underwater detection, ranging, communications, and imaging.

- Modulate intensity of lidar laser signal with radar (RF) waveforms
- Recover radar waveform from received lidar optical signal
- Apply coherent detection and other radar techniques to process received signal.

**Objectives:** Enhance hybrid lidar-radar performance:

- Develop and evaluate various digital signal processing (DSP) algorithms that will enhance hybrid lidar-radar performance in a variety of underwater environments.
- Implement algorithms via DSP hardware:
  - dynamically reconfigured via software (accomplish multiple missions with a single sensor)
  - real-time processing
  - reduced loss/temperature sensitivity





# Approach and Challenges



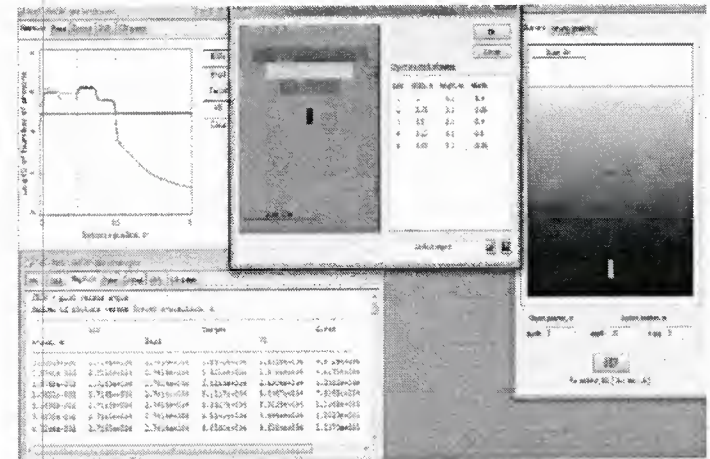
## Approach:

- Leverage algorithms that are widely used in radar and wireless communications
  - Spatial filtering
  - Frequency domain reflectometry
  - Blind signal separation

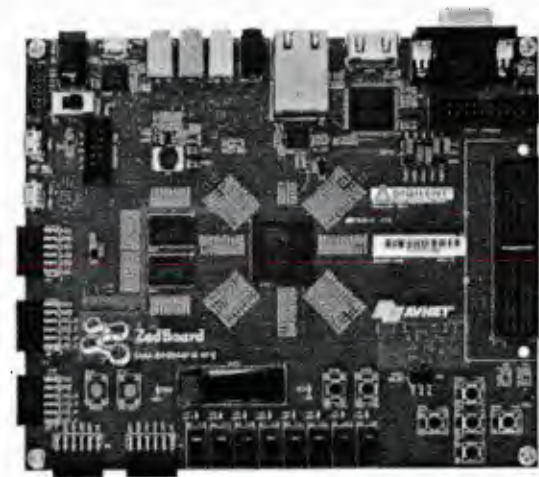
## Challenges:

- The underwater propagation channel is very different than the above-water environment
  - Use an underwater (UW) optical propagation model, Rangefinder, to generate simulated data to test DSP algorithms
- Many COTS DSP hardware platforms (e.g. software defined radios) are suitable for above-water radar communications but lack performance for UW light detection and ranging
  - Utilize FPGAs tailored for application

## Rangefinder



## Xilinx Zynq FPGA Platform



# Performance Goals

Simultaneously achieve:

high range resolution, range accuracy, range precision, and unambiguous range

## 1. Range resolution

- Indicates ability to resolve closely spaced targets

## 2. Range accuracy

- Indicates how close measurements are to the true range value

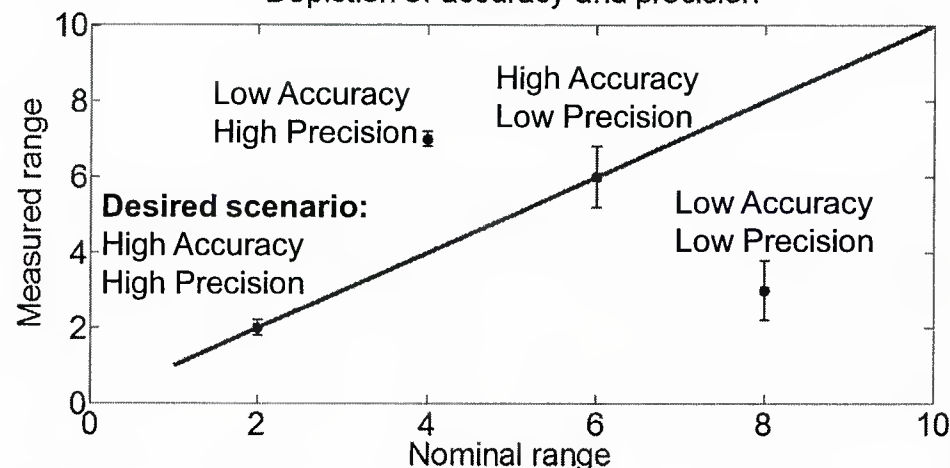
## 3. Range precision

- Indicates how closely multiple measurements are clustered together

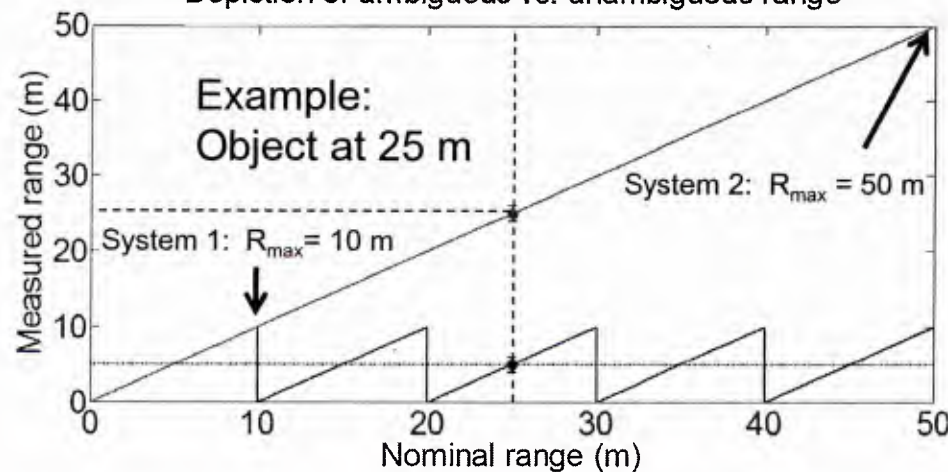
## 4. Unambiguous range

- $R_{max}$  indicates maximum distance at which true range is determined with no ambiguity

Depiction of accuracy and precision



Depiction of ambiguous vs. unambiguous range





# Progress and Activity

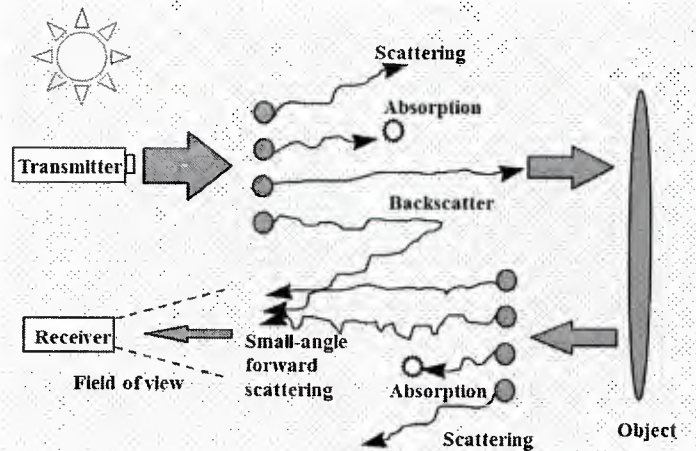


- Project start: June 2011
- Year 1
  - Participated in ONR NREIP program at NAVAIR
  - Assisted with water tank experiments
  - Characterized software defined radios
  - Identified, validated new lidar backscatter reduction technique: spatial filter
- Year 2
  - Participated in ONR NREIP program at NAVAIR
  - Spatial filter experiments
  - Identified new ranging technique: frequency-domain reflectometry
  - Identified new backscatter reduction technique: blind signal separation
- Summer 2013 (planned)
  - Participate in ONR NREIP program at NAVAIR
  - Thorough evaluation of new techniques
  - Validate new techniques with laboratory experiments
- Publications
  - "Underwater Laser Rangefinder," Proceedings of SPIE 2012, Ocean Sensing and Monitoring IV, Volume 8372
  - "Techniques to enhance the performance of hybrid lidar-radar ranging systems," Proceedings of MTS/IEEE Oceans 2012
  - "Technique to Extend Unambiguous Range of Hybrid Lidar-Radar Systems," Proceedings of MTS/IEEE Oceans 2013 (submitted)

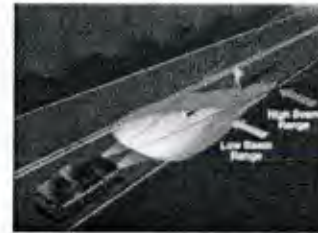


# Light propagation in water

- Absorption decreases the total signal level at the receiver
- Scattering degrades image contrast, resolution, and reduces range accuracy



## Absorption vs. Scatter-Limited Performance



Absorption-limited  
detection – more light,  
more range



Scatter-limited  
detection – more light,  
more 'clutter'

- Although absorption and scattering are two separate phenomena, their effects on water conditions are often combined together into a single parameter, the attenuation coefficient  $c$  (units:  $m^{-1}$ )
- Beam attenuation in water follows an exponential decay law, where  $cz$  is the number of attenuation lengths (a.l.) :

$$P(c, z) = P_0 \exp(-cz)$$

After traveling one attenuation length, the optical beam is attenuated by a factor of  $1 - \frac{1}{e} \approx 63.21\%$

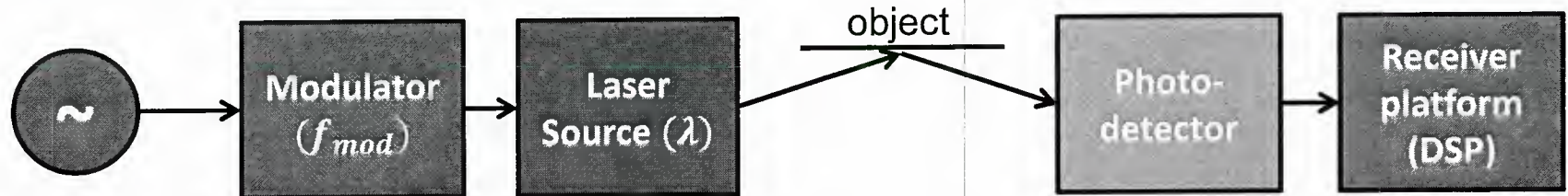
- We are focusing on enhancing performance in scatter-limited scenarios



# Three ways to improve performance in backscatter-limited scenarios



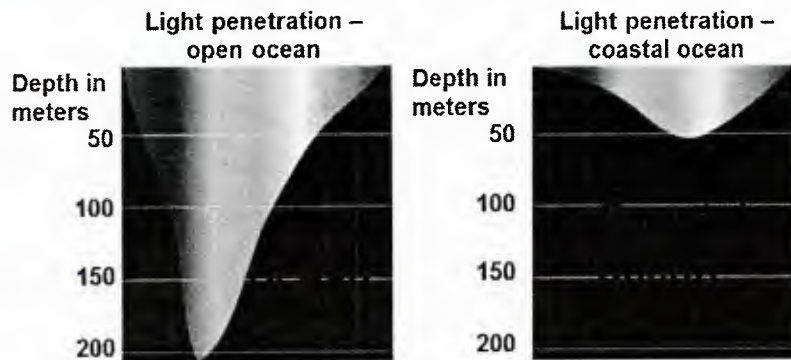
Simplified lidar-radar system



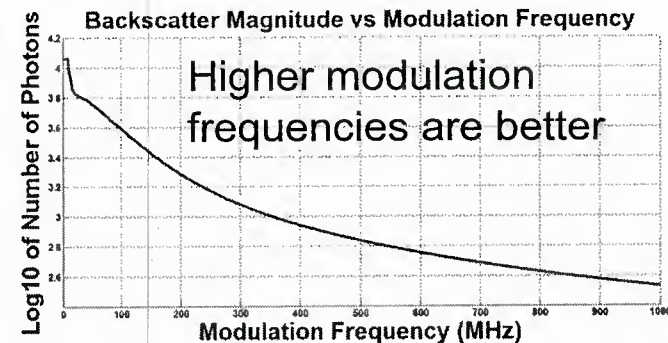
Radar signal generator

Radar receiver

## 1. Wavelength Selection ( $\lambda$ )

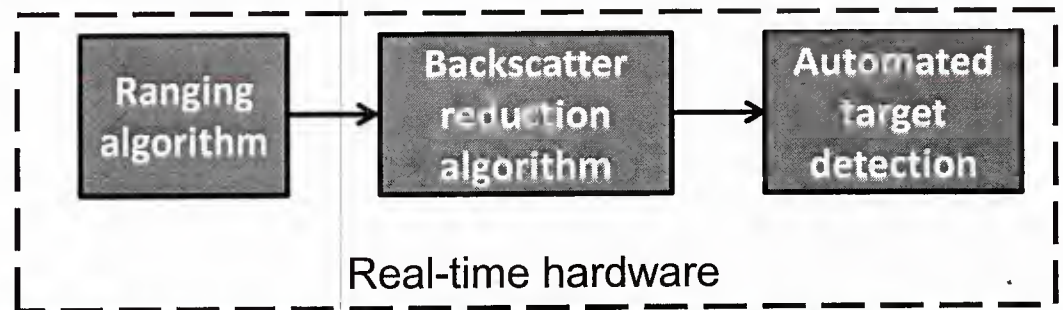


## 2. Modulation Frequency Selection ( $f_{mod}$ )



## 3. Digital Signal Processing (DSP)

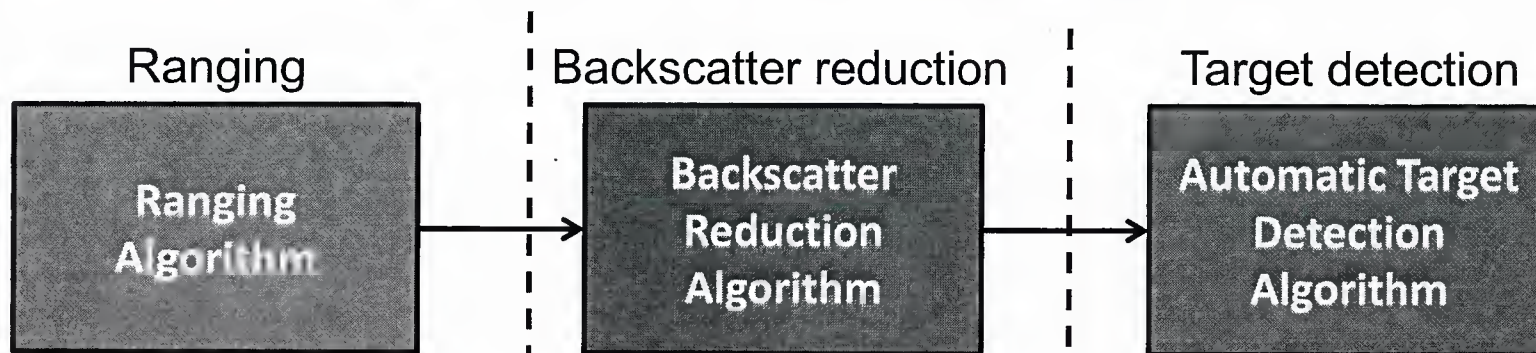
Our focus is to apply DSP algorithms to the receiver platform in order to **improve performance by processing the received signal.**





# Technical Results Overview

Goal: automatically detect a target and calculate range  
**without** any *a priori* knowledge



Approaches:

1. Single/Dual Tone

2. Frequency Domain Reflectometry

Spatial Filter

Blind Signal Separation

Phase to Range

Peak Detection

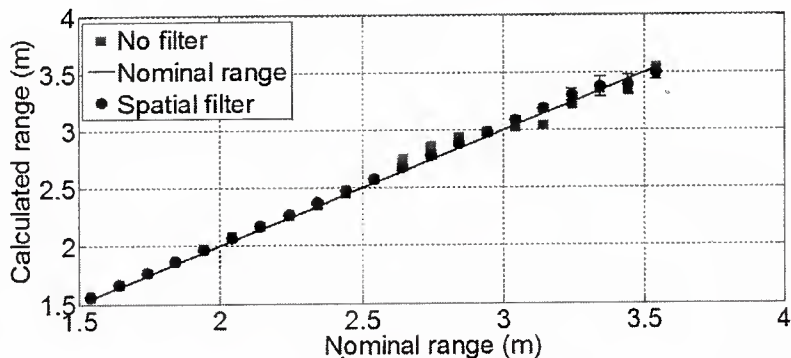


# Approach #1: Spatial Filter Results

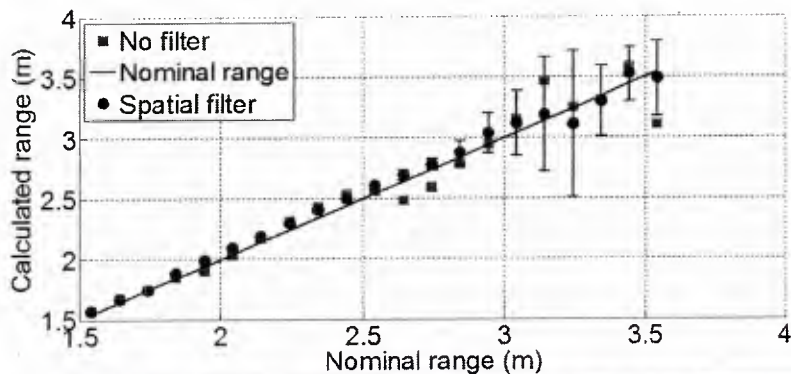


Results from 2012 Experiments,  $c = 2.5 \text{ m}^{-1}$

Single-tone ranging with  $f_m = 140 \text{ MHz}$

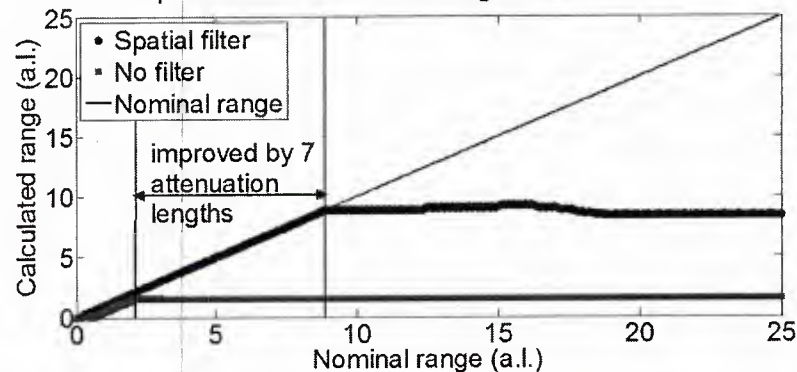


Dual-tone ranging with  $f_1 = 140 \text{ MHz}$ ,  $f_2 = 180 \text{ MHz}$

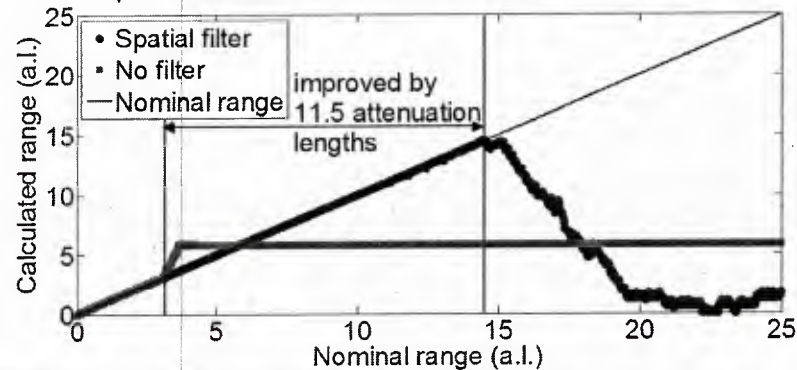


## Simulation of Theoretical Performance

Spatial filter simulation for single-tone at 140 MHz



Spatial filter simulation for dual-tone at 140 and 180 MHz

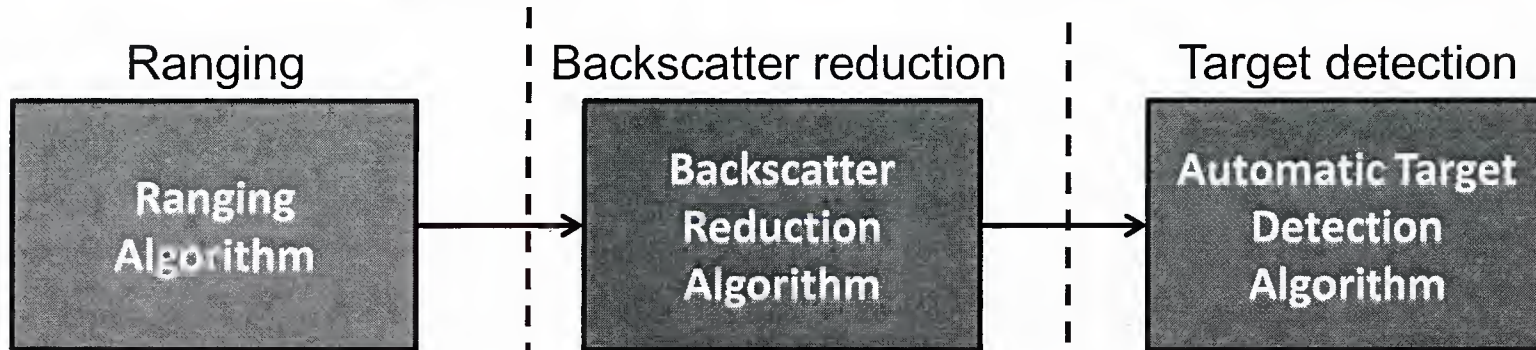


Range Algorithm	Unambiguous range	Range precision	Range Improvement with Spatial Filtering
Single-tone 140 MHz	0.80 m	2.65 cm	7 a.l.
Dual-tone 140, 180 MHz	2.81 m	12.40 cm	11.5 a.l.



# Technical Results Overview

Goal: automatically detect a target and calculate range  
**without** any *a priori* knowledge



Approaches:

1. Single/Dual Tone

2. Frequency Domain Reflectometry

Spatial Filter

Blind Signal Separation

Phase to Range

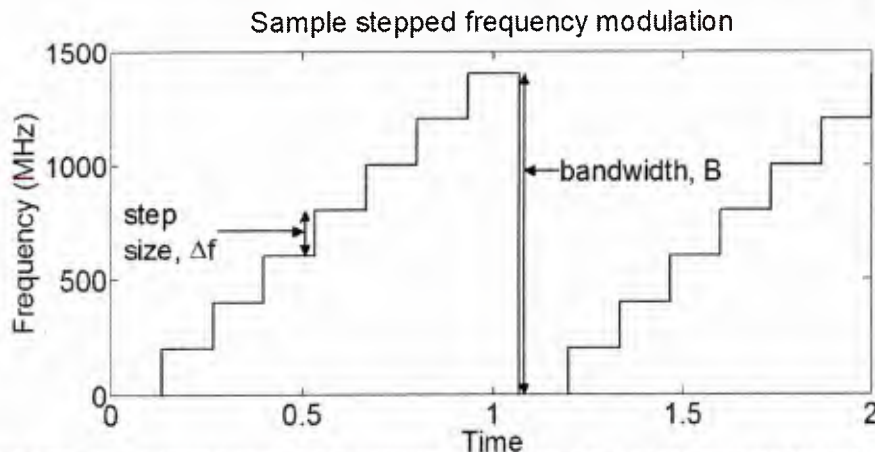
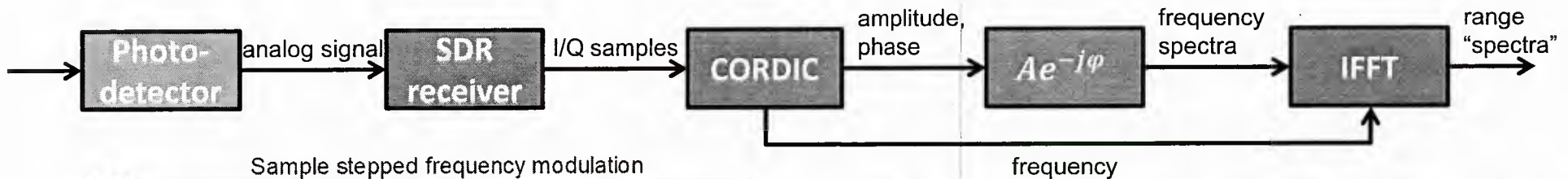
Peak Detection



# Approach #2 Ranging Algorithm: Frequency-Domain Reflectometry (FDR)



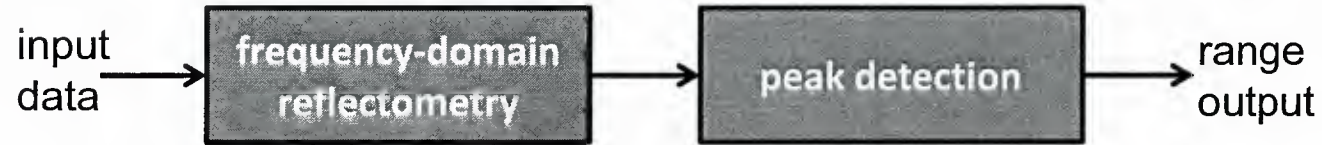
- FDR is a stepped frequency technique developed to detect faults in RF and fiber optic cables
- Small step size can lead to large unambiguous range performance
- Requires a large bandwidth to achieve comparable precision to CW methods



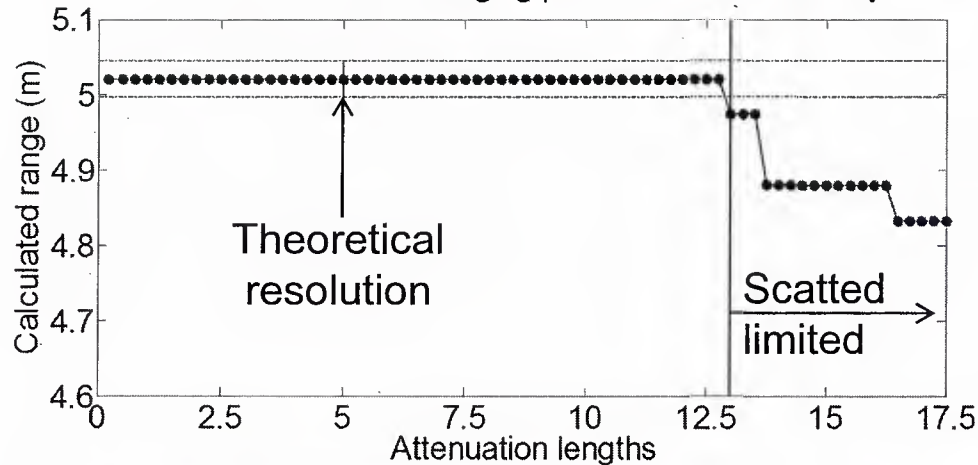
Parameter	Equation
Unambiguous range	$R_{max} = \frac{v}{2\Delta f}$
Range precision	$\delta R = \frac{v}{4B}$



# Approach #2: FDR Simulated Results with Automated Target Detection



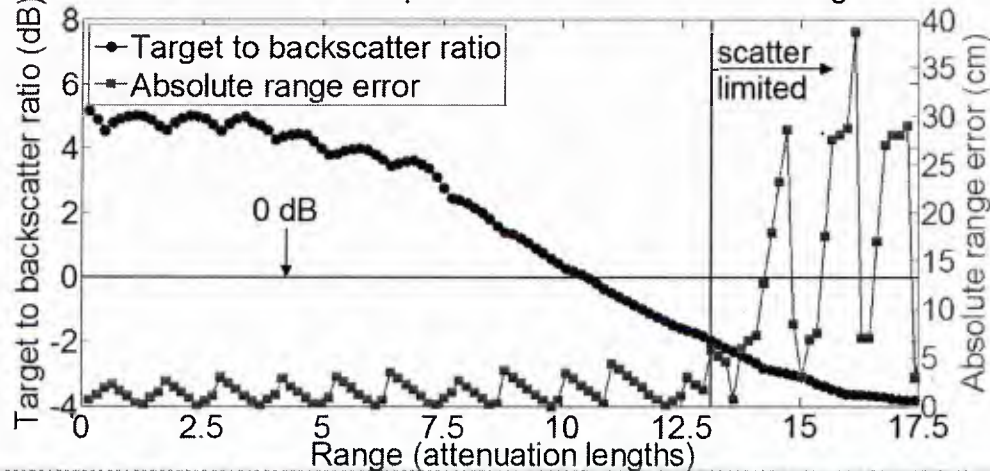
Simulation of FDR ranging performance vs. turbidity



**Simulation:** Fixed target range, varying turbidity.

- BW = 1.2 GHz;
- $\Delta f = 1.17$  MHz;
- $\delta R = 4.69$  cm;
- $R_{max} = 48.0$  m
- No backscatter reduction processing

Simulation of FDR performance as function of range



**Results:** automated target detection works to 13 a.l. corresponding to target-to-backscatter ratios of -2 dB

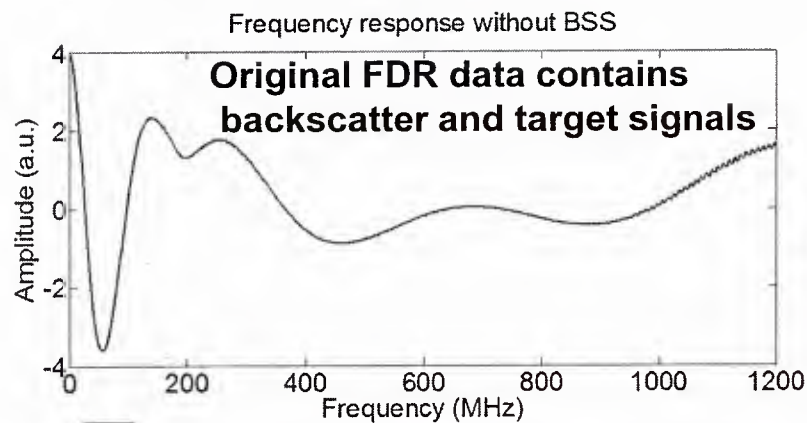
**Next step:** apply blind signal separation to reduce backscatter



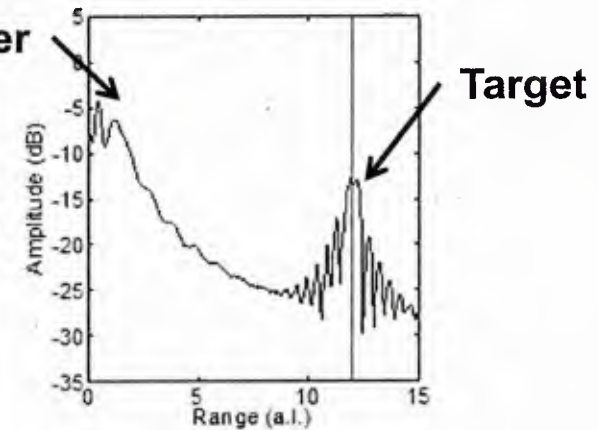
# Approach #2: Blind Signal Separation for Backscatter Reduction



- Photons reflected from objects and backscatter in the scene are recorded as a single "mixed" lidar return
- Applying blind signal separation (BSS), the target and scatter components of the return can be separated

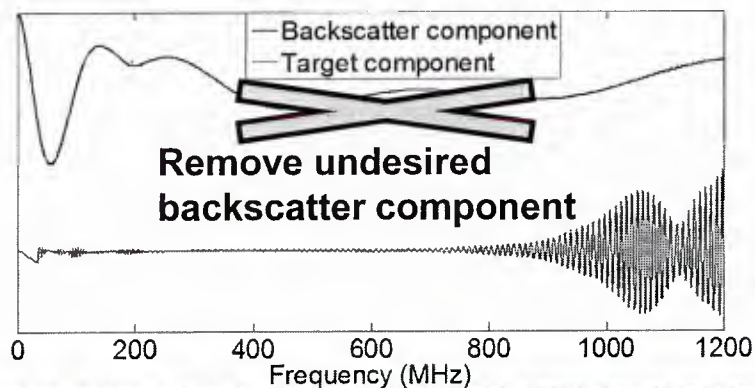


**Backscatter**

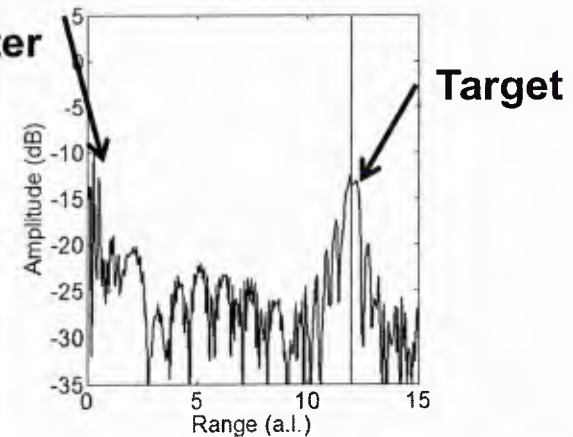


**BSS separates the signal into separate backscatter and target signals**

Frequency response of BSS components



**Reduced Backscatter**





# Blind Signal Separation (BSS) Math Overview



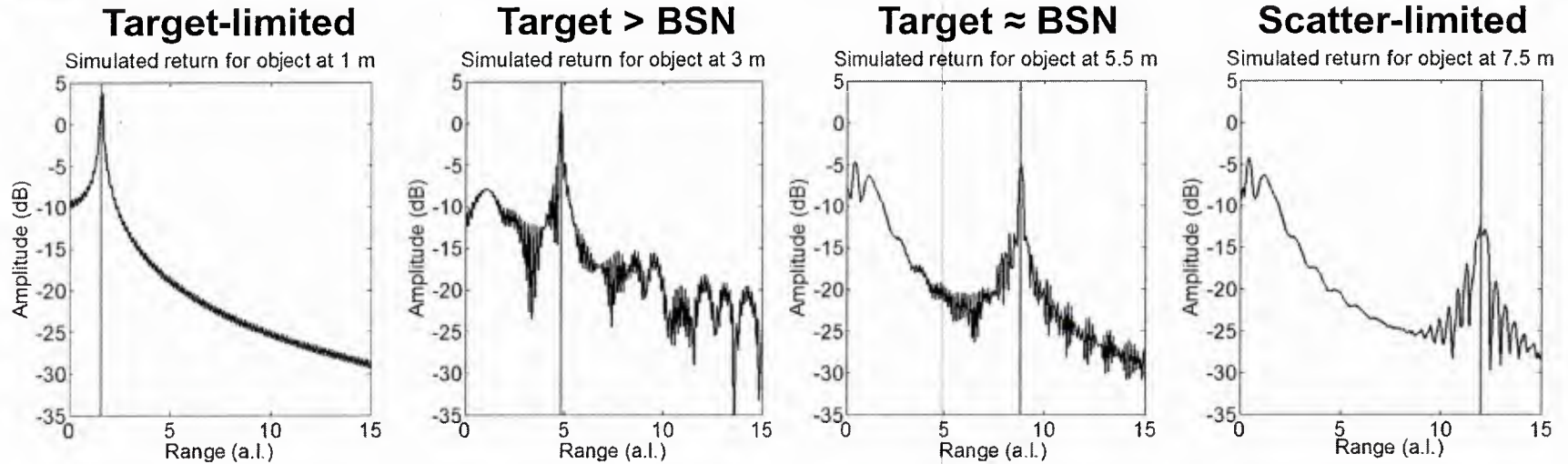
- Objective: Separate observations of several signals into the independent signal components based on their statistics
- Model:  $X = AS$   
 $X$ : observation matrix,  $A$ : "mixing" matrix,  $S$ : source matrix
- Methodology: Select a statistical property. Adaptively learn a weight matrix  $W \approx A^{-1}$  based on  $X$ .  $W$  should maximize separation based on the desired statistical property. At convergence, source components are estimated as  $\hat{S} = WX \approx A^{-1}X$
- Challenges:
  - Choice of statistical property
  - Choice of convergence criteria
  - Estimation of number of sources
  - Choice of number of observations
  - Computational complexity



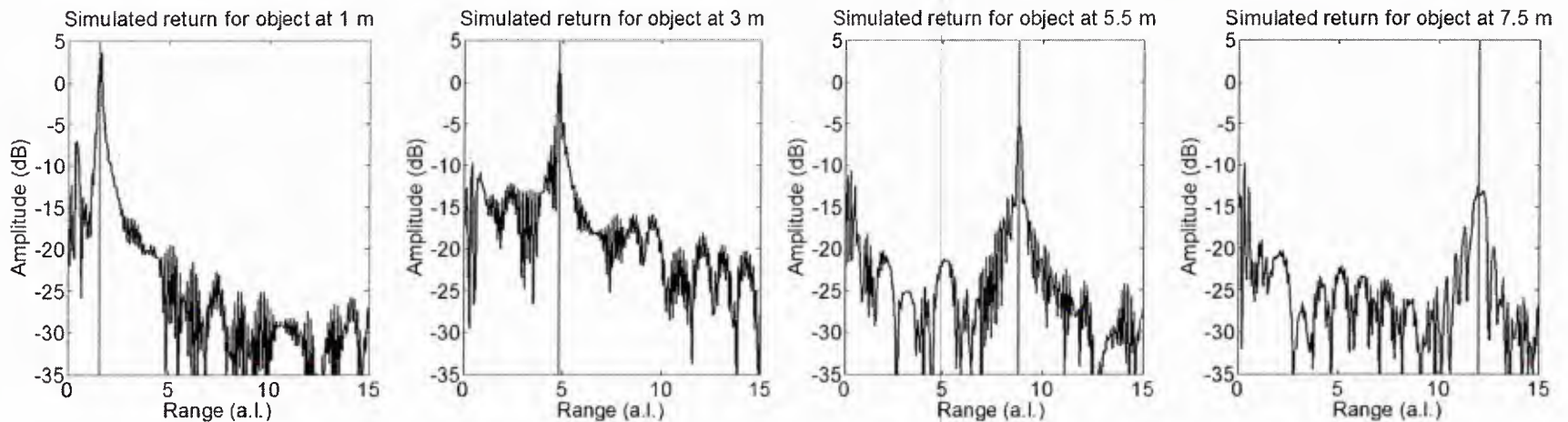
# Approach #2: FDR Simulated Results with and without Backscatter (BSN) Reduction



no backscatter reduction



blind signal separation



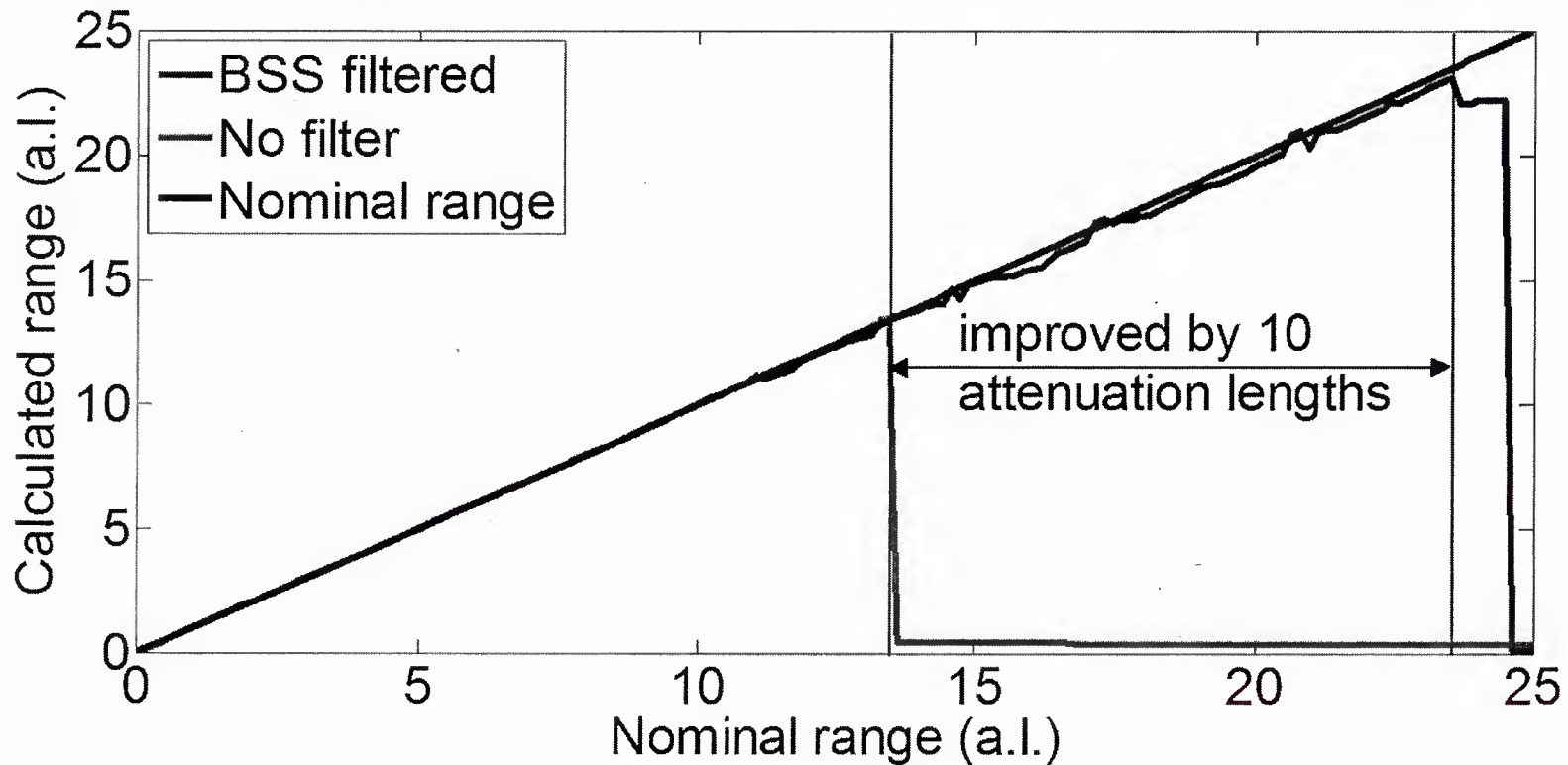
Green lines indicate actual target position  
Range bin size: 9.38 cm; Turbidity:  $c = 1.6 \text{ m}^{-1}$



# Approach #2: FDR with BSS and Automated Signal Detection



BSS simulation for FDR w 1.2 GHz BW and 1024 tones



$$c = 1.6 \text{ m}^{-1}; \text{ BW} = 1.2 \text{ GHz}; \Delta f = 1.17 \text{ MHz}$$
$$\delta R = 4.69 \text{ cm}; R_{max} = 48.0 \text{ m}$$



# Real-Time Implementation

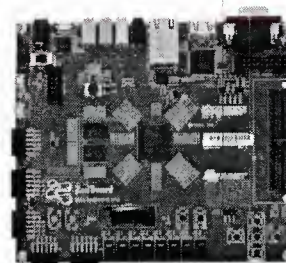
- Several basic building blocks have been implemented on real-time DSP hardware:
- Baseband demodulation
  - Decomposes RF signal into two orthogonal vectors
- CORDIC (COordinate Rotation Digital Computer)
  - Given two vectors, finds the magnitude and phase angle of the resultant vector
  - The phase angle can be used to calculate range
- Instantaneous frequency demodulator
  - Calculates the frequency of the input signal

Example: demodulation of sinusoidal frequency modulated signal

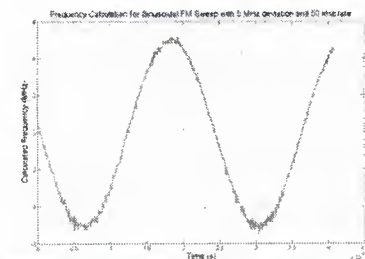
1. System design



2. Implementation



3. Calculation





# Technique Comparison



## Approach 1

### Single- and Dual-Tone Ranging

- + short dwell time
- + very high precision
- single range result
- tradeoff between  $f_{mod}$  and  $R_{max}$

### Spatial Filter

- + computationally simple
- + single parameter
- logistically complicated
- implementation dependent on  $f_{mod}$

## Approach 2

### Frequency-Domain Reflectometry

- + large unambiguous range
- + “range spectra”
- large bandwidth
- long dwell time

### Blind Signal Separation

- + logistically simple
- + implementation independent of  $f_{mod}$
- computationally complicated
- many parameters



# Summary



- Significant progress has been made in developing a digital signal processing approach to enable hybrid lidar-radar ranging systems to perform automatic target detection:
  - Ranging: frequency-domain reflectometry technique provides large unambiguous range
  - Backscatter reduction: blind signal separation technique is able to separate the target and scatter returns
  - Target detection: simple peak detection algorithm is able to automatically detect target position
- Planned work
  - Experiments planned for summer 2013 to test performance of new technique as a function of range and turbidity
  - Continue to perform experiments with spatial filter method
  - MTS/IEEE Oceans Conference presentation in Fall 2013
  - Explore more sophisticated target detection algorithms that combine FDR and signal-tone approaches to improve precision
  - Develop real-time versions of each technique



# Background Slides



# Frequency-Domain Reflectometry (FDR) Overview



1. Transmit stepped frequency sweep with  $N$  tones
2. For each frequency  $f_i$ , record magnitude  $A_i$  and phase  $\varphi_i$
3. Construct complex vector  $S_i = A_i \exp(j\varphi_i)$
4. Calculate inverse Fourier transform of  $S_i$ :  
$$s(t) = \frac{1}{2\pi} \int S(f) \exp(2\pi f t) df$$
5. Peaks appearing in the time-domain can be converted to range by multiplying by the speed of light



# Frequency-Domain Reflectometry (FDR) Range Equation Derivation



- FDR range equations are based on applying Nyquist sampling theory in the frequency-domain
- Unambiguous range:
  - Frequency sample spacing:  $\Delta f$
  - Maximum sampling time:  $t_{max} = \frac{1}{\Delta f}$
  - Convert to range:  $R_{max} = \frac{v}{2} t_{max} = \frac{v}{2\Delta f}$
- Range precision:
  - Time bin size:  $\delta t = \frac{1}{2N} t_{max} = \frac{1}{2N\Delta f} = \frac{1}{2B}$
  - The factor of one-half is needed because the maximum error is half the size of a bin
  - Convert to range:  $\delta R = \frac{v}{2} \delta t = \frac{v}{4B}$



# Blind Signal Separation (BSS) Math Overview



- Objective: Separate observations of several signals into the independent signal components based on their statistics
- Model:  $X = AS$   
 $X$ : observation matrix,  $A$ : "mixing" matrix,  $S$ : source matrix
- To separate components based on variance:
  1. Calculate sample covariance matrix  $C = X^T X$
  2. Apply singular value decomposition:  
$$X = USV^T$$
  
 $U$ : projection of  $X$  onto eigenvectors of  $C$ ,  $S$ : diagonal matrix of eigenvalues of  $C$ ,  $V$ : eigenvectors of  $C$
  3. Remove undesired components by "zeroing-out" columns of  $U$  and corresponding rows of  $S$  to obtain  $U_0$  and  $S_0$
  4. Calculated filtered observations as  $X_{filt} = U_0 S_0 V^T$