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Coherence and Time-Delay Estimation for Sonar and Dual-Use Applications

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Reprint of a presentation made at the *Fourier Euroworkshop on Advanced Signal Processing*, 10-13 April 2000, Corfu, Greece.

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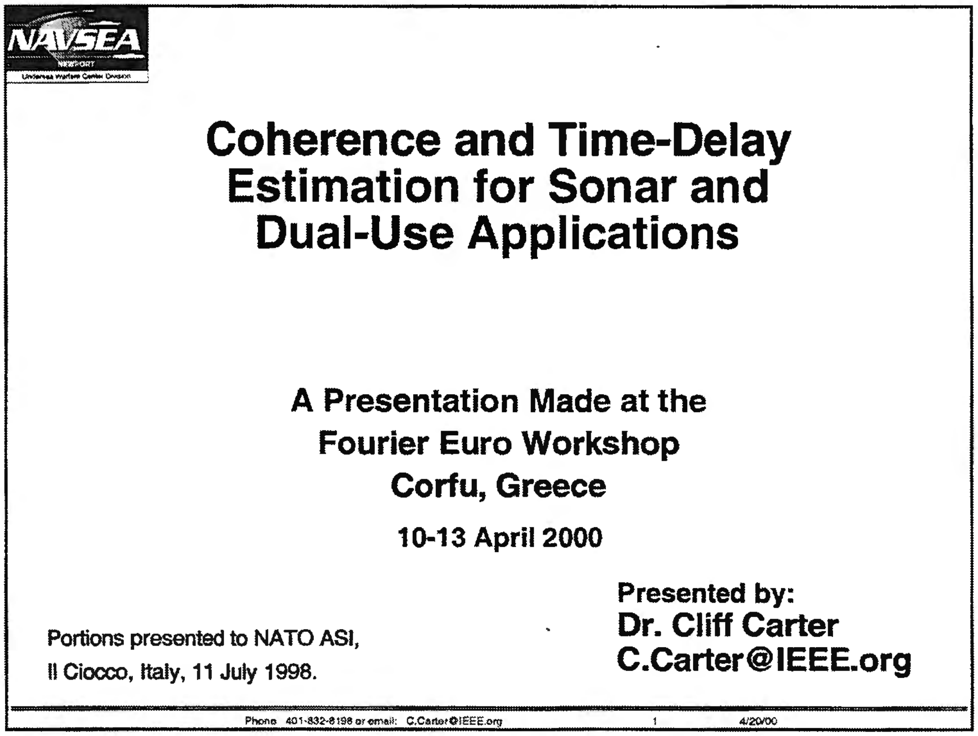

Coherence and Time-Delay Estimation for Sonar and Dual-Use Applications

A Presentation Made at the
Fourier Euro Workshop
Corfu, Greece

10-13 April 2000

Presented by:
Dr. Cliff Carter
C.Carter@IEEE.org

Portions presented to NATO ASI,
Il Ciocco, Italy, 11 July 1998.

Outline

- Purpose
- Applications
- Environment
- Sensors
- Processing
- Processors
- Displays
- Performance
- Future
- Summary
- Questions

Purpose of Talk

- Provide an overview of some of the signal processing techniques (including Coherence and Time-Delay Estimation that use Fourier Transforms) for underwater acoustic applications
- Stimulate thinking, experiments, and tests of technology developed for underwater acoustics for dual-use in other fields including bio-medicine, commercial fishing, fish monitoring and treaty compliance

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Selected Underwater Acoustic Applications

- Detection: Deciding if an object is present or absent
- Classification: Deciding the class or group of an object
- Localization: Measuring range, bearing, and depth
- Navigation: Determining, and controlling, position
- Communications: Transmitting and receiving acoustic information
- Control: Using a sound-activated release mechanism
- Position Marking: Beacons or Transponders
- Depth Sounding: Sending short pulses and timing bottom return
- Acoustic Speedometers: Using pairs of transducers to obtain speed

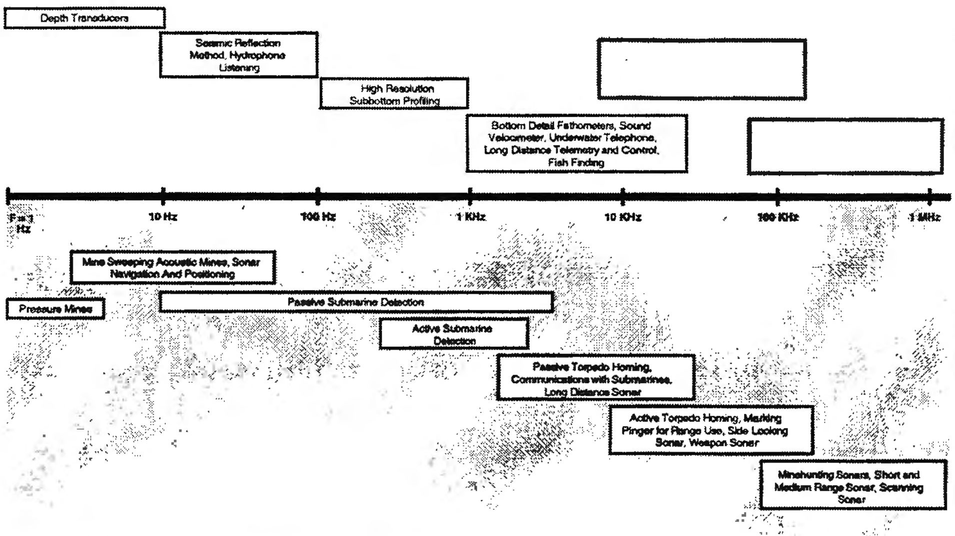
Source (modified): R.J. Urick, *Principles of Underwater Sound*, McGraw-Hill, New York, 1983.

Commercial Applications

- Fish Finders / Fish Herding
- Subbottom Geological Mapping
- Fish Population Estimation
- Environmental Monitoring
- Oil and Mineral Explorations
- River Flow Meter / Bathyvelocimeter
- Acoustic Holography
- Emergency Telephone
- Viscosimeter / Seismic Simulation and Measurement
- Acoustic Ship Docking System
- Ultrasonic Grinding / Drilling
- Sonar Calibration
- Biomedical Ultrasound (Active sonar)

Source (modified): R.J. Urick, *Principles of Underwater Sound*, McGraw-Hill, New York. 1983.

Commercial Applications



Depth Transducers

Seismic Reflection Method, Hydrophone Listening

High Resolution Subbottom Profiling

Bottom Detail Fathometers, Sound Velocimeter, Underwater Telephone, Long Distance Telemetry and Control, Fish Finding

Mine Sweeping Acoustic Mines, Sonar Navigation And Positioning

Pressure Mines

Passive Submarine Detection

Active Submarine Detection

Passive Torpedo Homing, Communications with Submarines, Long Distance Sonar

Active Torpedo Homing, Marking Pinger for Range Use, Side Looking Sonar, Weapon Sonar

Minehunting Sonars, Short and Medium Range Sonar, Scanning Sonar

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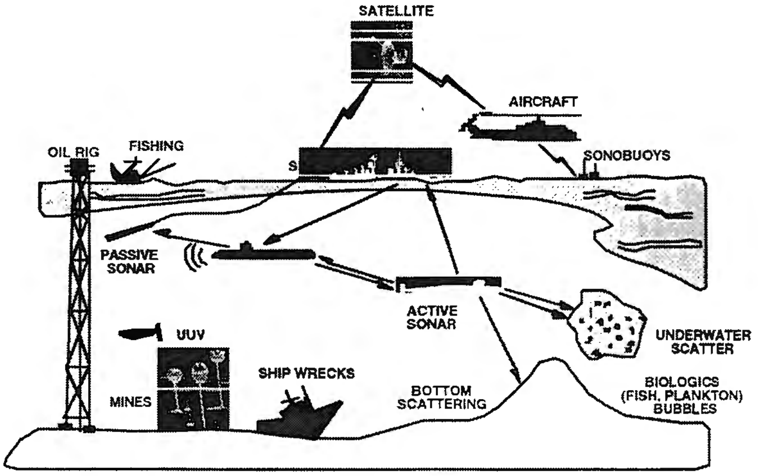
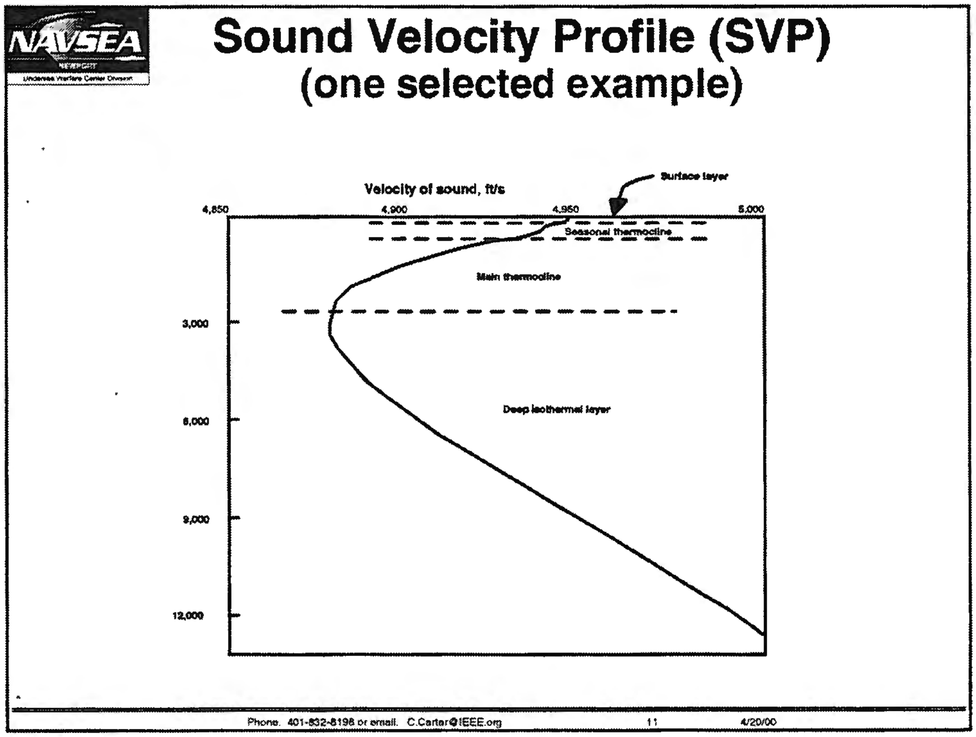
The Underwater Acoustic Environment





Sound Velocity Profile (SVP)
(one selected example)

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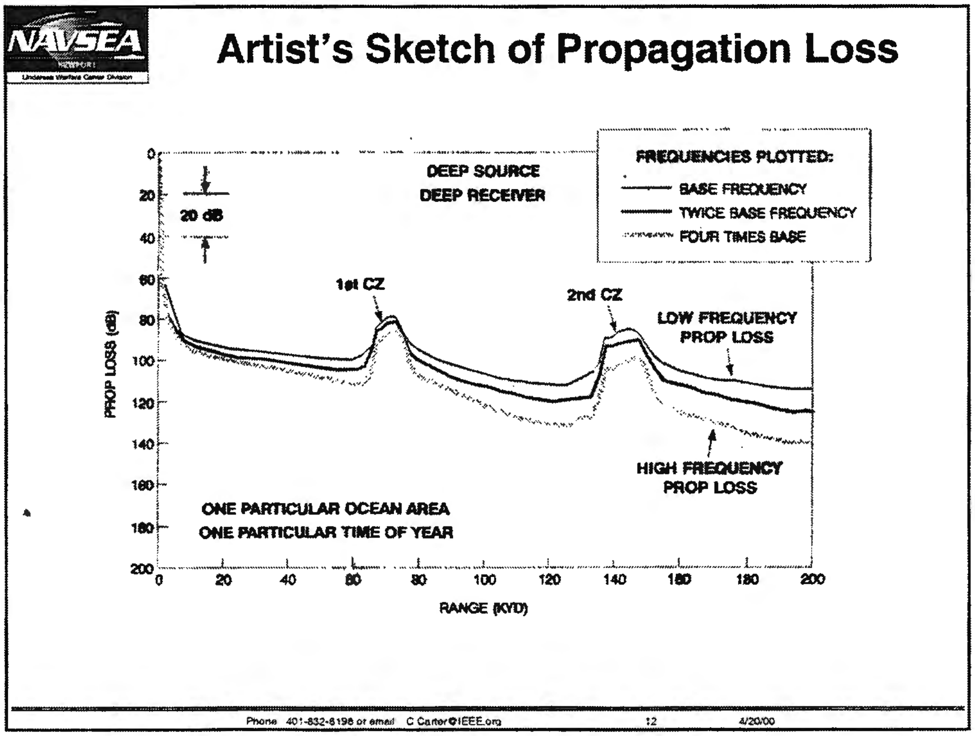

Artist's Sketch of Propagation Loss

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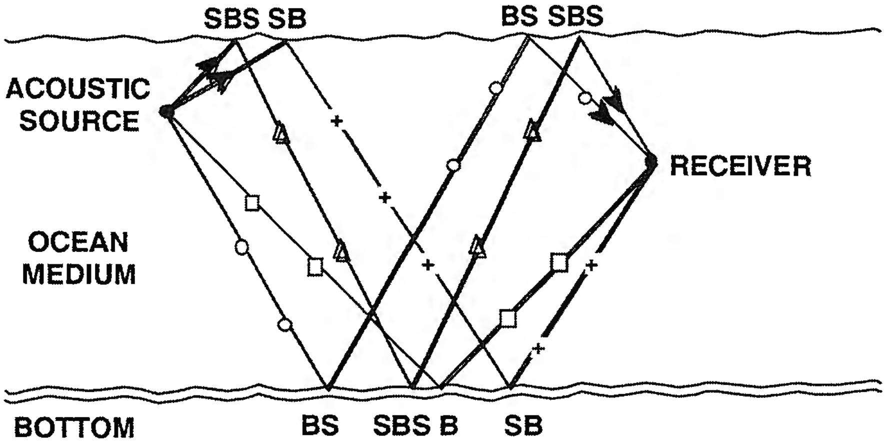
Dominant Ray-Trace Paths
(beyond direct path and inside the first CZ)



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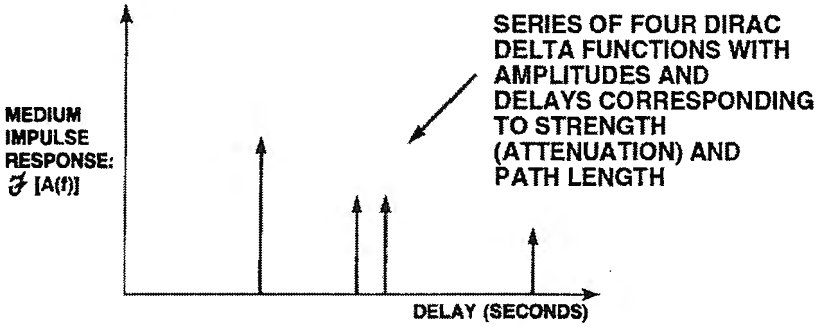
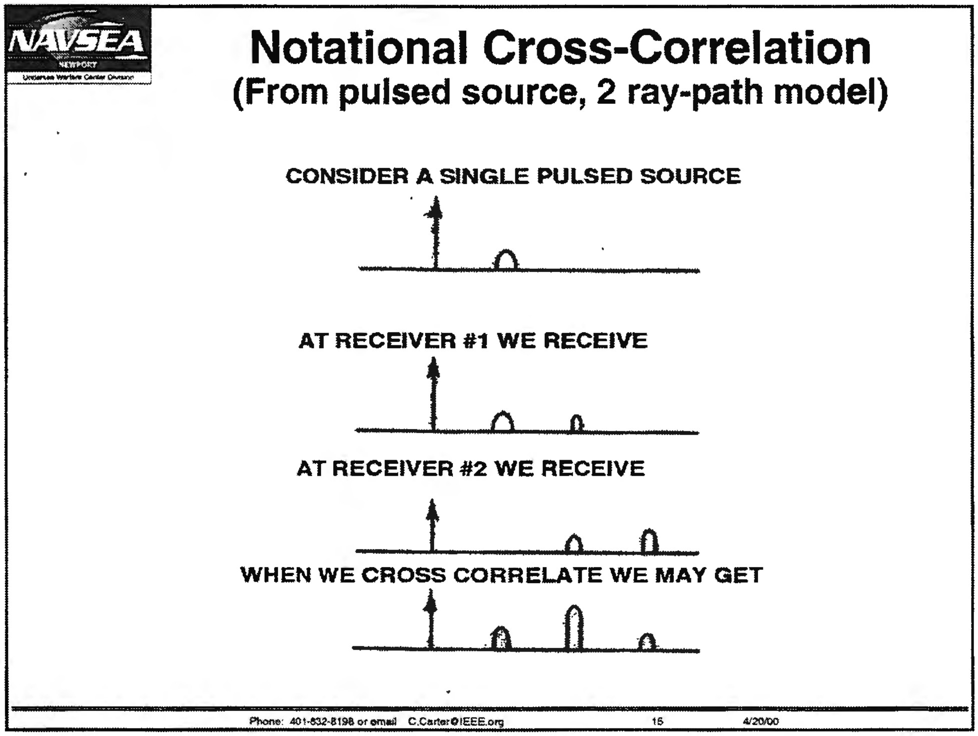
Medium Impulse Response
(Fourier Transform of Ocean Transfer Function)





Notational Cross-Correlation

(From pulsed source, 2 ray-path model)

CONSIDER A SINGLE PULSED SOURCE

AT RECEIVER #1 WE RECEIVE

AT RECEIVER #2 WE RECEIVE

WHEN WE CROSS CORRELATE WE MAY GET

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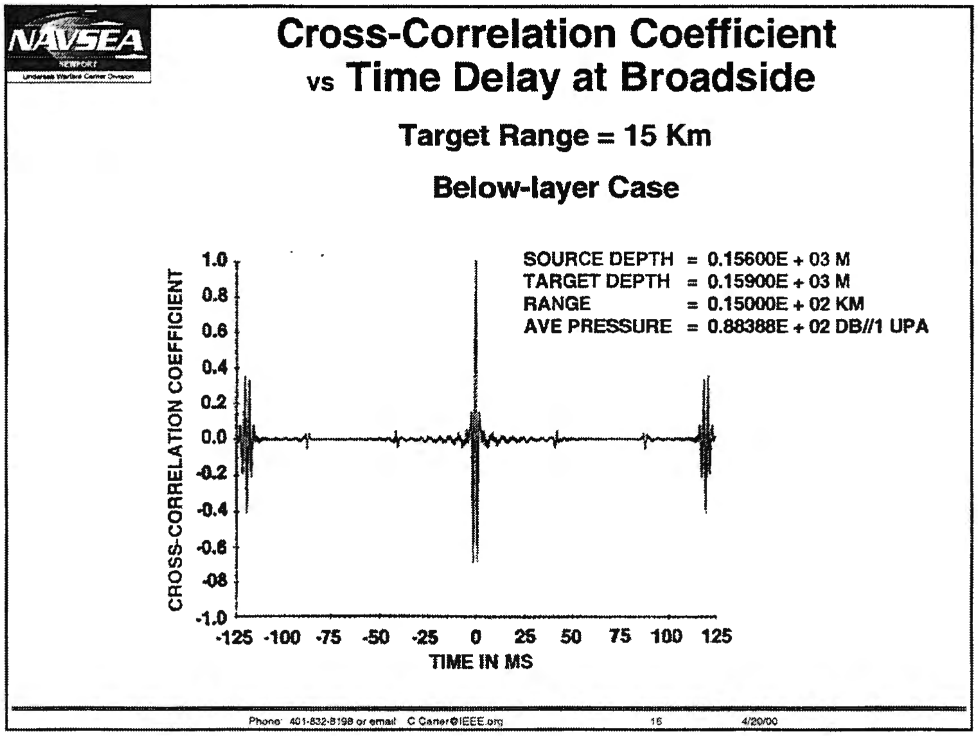

Cross-Correlation Coefficient vs Time Delay at Broadside

Target Range = 15 Km

Below-layer Case

SOURCE DEPTH = 0.15600E + 03 M
TARGET DEPTH = 0.15900E + 03 M
RANGE = 0.15000E + 02 KM
AVE PRESSURE = 0.88388E + 02 DB//1 UPA

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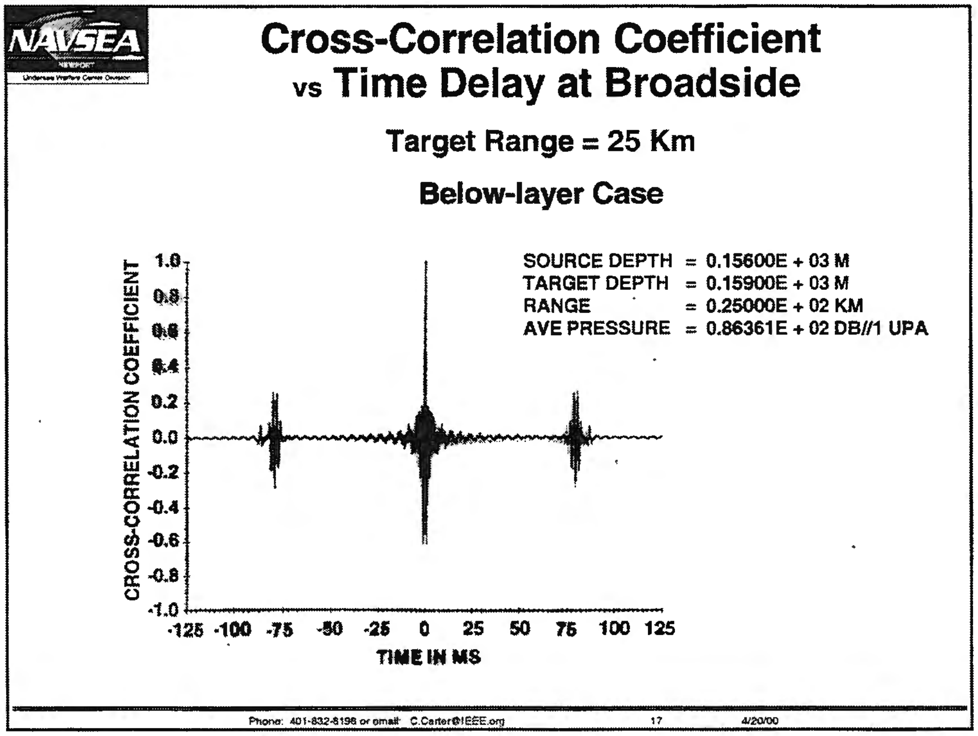

Cross-Correlation Coefficient vs Time Delay at Broadside

Target Range = 25 Km

Below-layer Case

SOURCE DEPTH = 0.15600E + 03 M
TARGET DEPTH = 0.15900E + 03 M
RANGE = 0.25000E + 02 KM
AVE PRESSURE = 0.86361E + 02 DB//1 UPA

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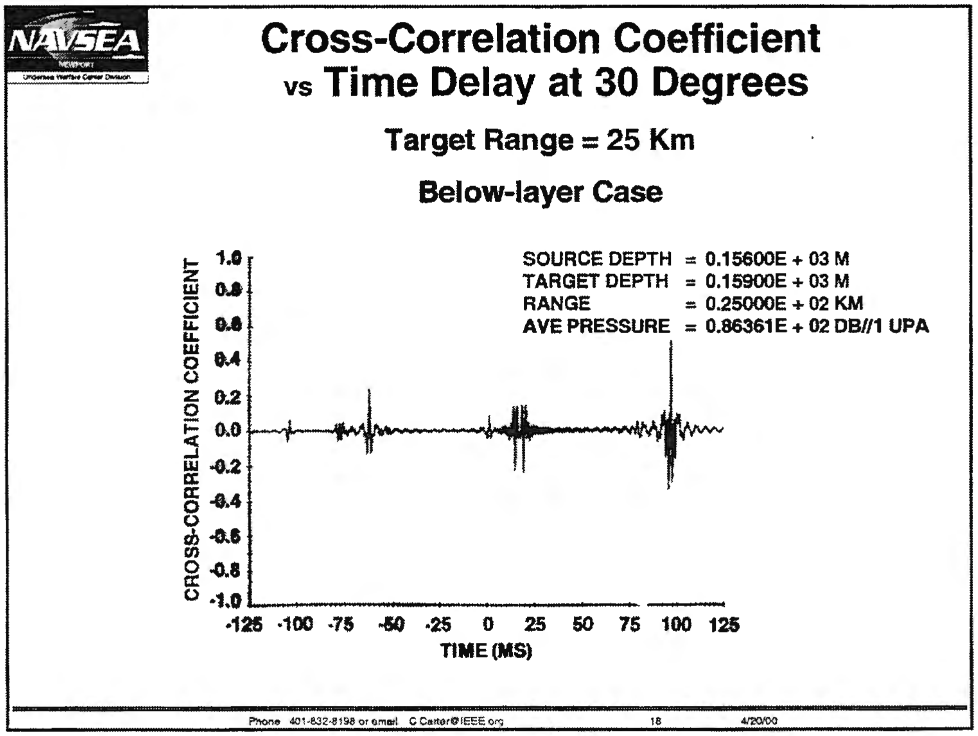

Cross-Correlation Coefficient vs Time Delay at 30 Degrees

Target Range = 25 Km

Below-layer Case

SOURCE DEPTH = 0.15600E + 03 M
TARGET DEPTH = 0.15900E + 03 M
RANGE = 0.25000E + 02 KM
AVE PRESSURE = 0.86361E + 02 DB//1 UPA

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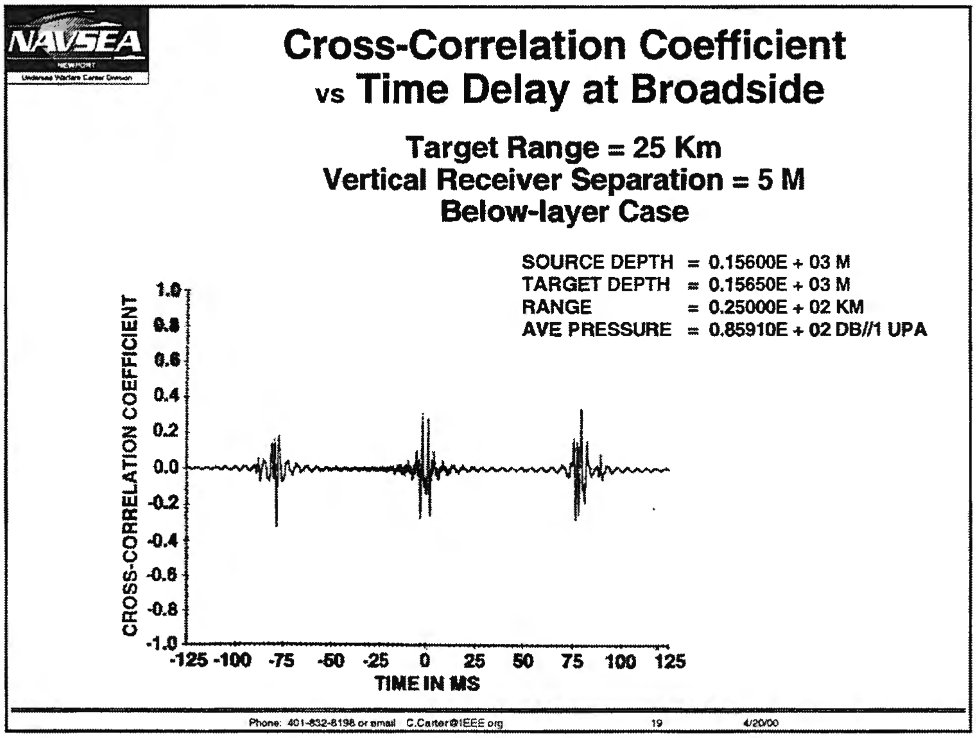

Cross-Correlation Coefficient vs Time Delay at Broadside

Target Range = 25 Km
Vertical Receiver Separation = 5 M
Below-layer Case

SOURCE DEPTH = 0.15600E + 03 M
TARGET DEPTH = 0.15650E + 03 M
RANGE = 0.25000E + 02 KM
AVE PRESSURE = 0.85910E + 02 DB//1 UPA

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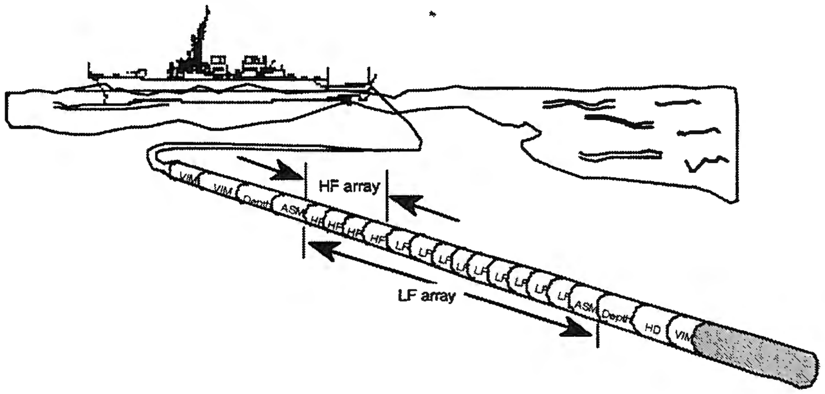
Artist Depiction of Towed Streamer

(passive sonar and active receiver for oil exploration)



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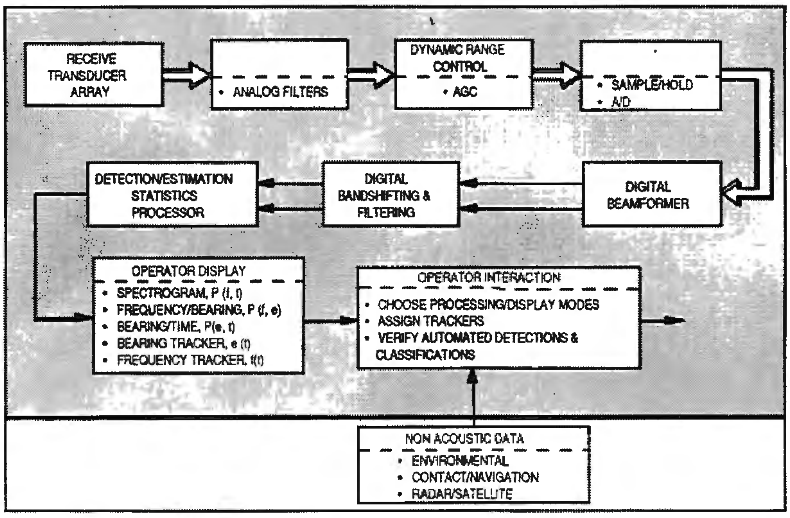
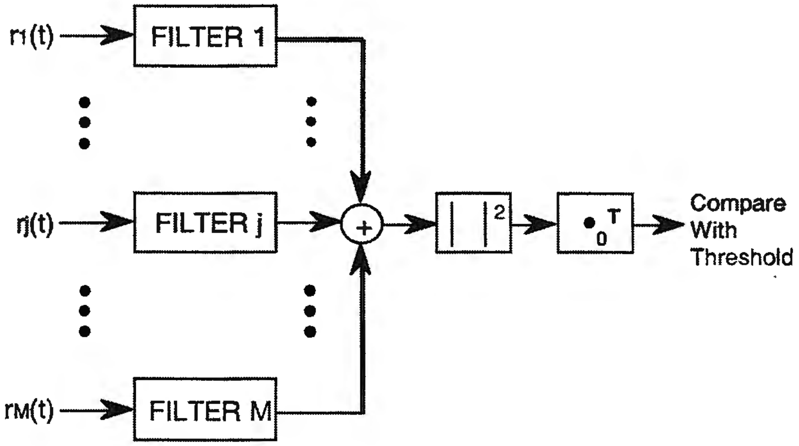
Conceptual Processing Chain



Energy Detector



$r_1(t)$ FILTER 1

$r_j(t)$ FILTER j

$r_M(t)$ FILTER M

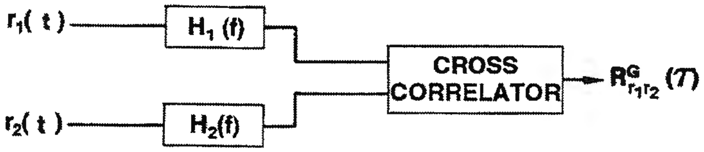
$+$

$|\ |^2$

$\int_0^T$

Compare With Threshold

GCC Approach for TDE



$r_1(t)$ $H_1(f)$

$r_2(t)$ $H_2(f)$

CROSS CORRELATOR

$R^G_{r_1r_2}(\tau)$

GCC FUNCTION

$$R^G_{r_1r_2}(\tau) = \int_{-\infty}^{\infty} W(f)\, G_{r_1r_2}(f)\, e^{j2\pi f\tau}\, df \;= \int_{-\infty}^{\infty} W_\phi(f)\, e^{j\phi(f)}\, e^{j2\pi f\tau}\, df$$

WEIGHTING FUNCTION

$$W(f) = H_1(f)\, H_2^*(f), \quad W_\phi(f) = |G_{r_1r_2}(f)|\; W(f)$$

GCC = Generalized Cross-Correlation
GCC = Fourier Transform of Weighted Cross Power Spectrum
TDE = Time Delay Estimation

Common Weighting Functions

METHOD	$W(f) = H_1(f)\,H_2{}^*(f)$	$W_\phi(f) = W(f)\,\lvert G_{r_1r_2}(f)\rvert$
SCC	1	$\lvert G_{r_1r_2}(f)\rvert$
ROTH	$1/G_{r_1r_1}(f)$	$\lvert G_{r_1r_2}(f)\rvert / G_{r_1r_1}(f)$
WIENER PROCESSOR	$C_{r_1r_2}(f)$	$C_{r_1r_2}(f)\,\lvert G_{r_1r_2}(f)\rvert$
SCOT	$1/\sqrt{G_{r_1r_1}(f)\,G_{r_2r_2}(f)}$	$\sqrt{C_{r_1r_2}(f)}$
PHAT	$1/\lvert G_{r_1r_2}(f)\rvert$	1
ML	$\dfrac{C_{r_1r_2}(f)}{[1 - C_{r_1r_2}(f)]\lvert G_{r_1r_2}(f)\rvert}$	$\dfrac{C_{r_1r_2}(f)}{1 - C_{r_1r_2}(f)}$

$$C_{r_1r_2}(f) = \frac{\lvert G_{r_1r_2}(f)\rvert^2}{G_{r_1r_1}(f)\,G_{r_2r_2}(f)}$$

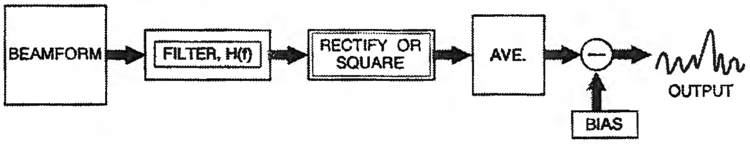
Filter Options

FILTER NAME	FREQUENCY DEPENDENCE, $H(f)\,H^*(f)$
STANDARD CC	1
ECKART (LOW SNR)	$S(f) / N^2(f) \rightarrow 1 / N(f)$, for $(S=N)$
PHAT	$1 / S(f)$
SCOT	$1 / [S(f) + N(f)] \rightarrow 1 / N(f)$ (LOW SNR)
ECKART (HIGH SNR)	$1 / [2N(f)]$

ECKART OPTIMUM IN THEORY;
SCOT/PHAT ADAPTIVE RESULTS ENCOURAGING;
NOISE AND SIGNAL SPECTRA MUST BE KNOWN OR ESTIMATED

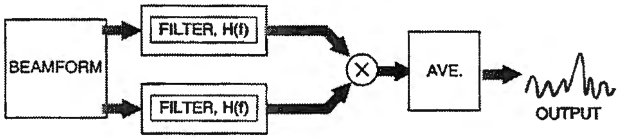
ED vs. GCC

ENERGY DETECTOR (ED) - 1.5 dB Better in Theory



IMPORTANT:
NON LINEAR-
TIME VARYING
DISPLAY
NORMALIZATION
MAKES TESTING
DIFFICULT

GENERALIZED CROSS-CORRELATOR (GCC) - Better in Practice



IMPORTANT:
ZERO MEAN
NOISE ONLY OUTPUT
MAKES
THRESHOLD SETTING
EASY

FOCUSED AND MATCHED BEAMFORMERS MAKE RAPID LOCALIZATION POSSIBLE

ROLE OF FILTERS TO BE DISCUSSED

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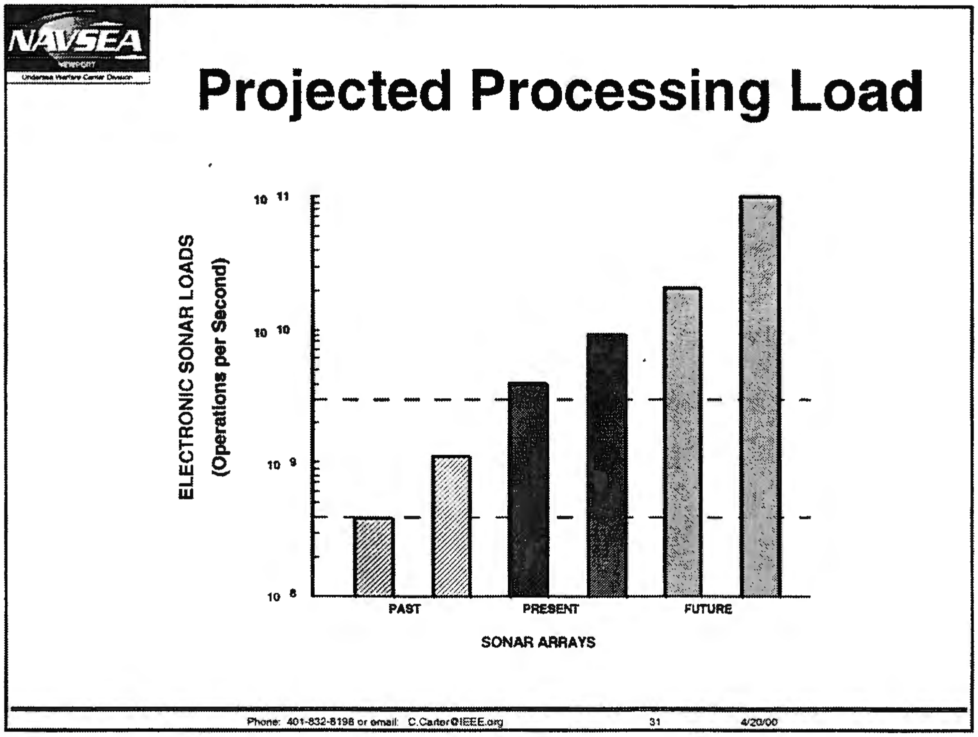

Projected Processing Load

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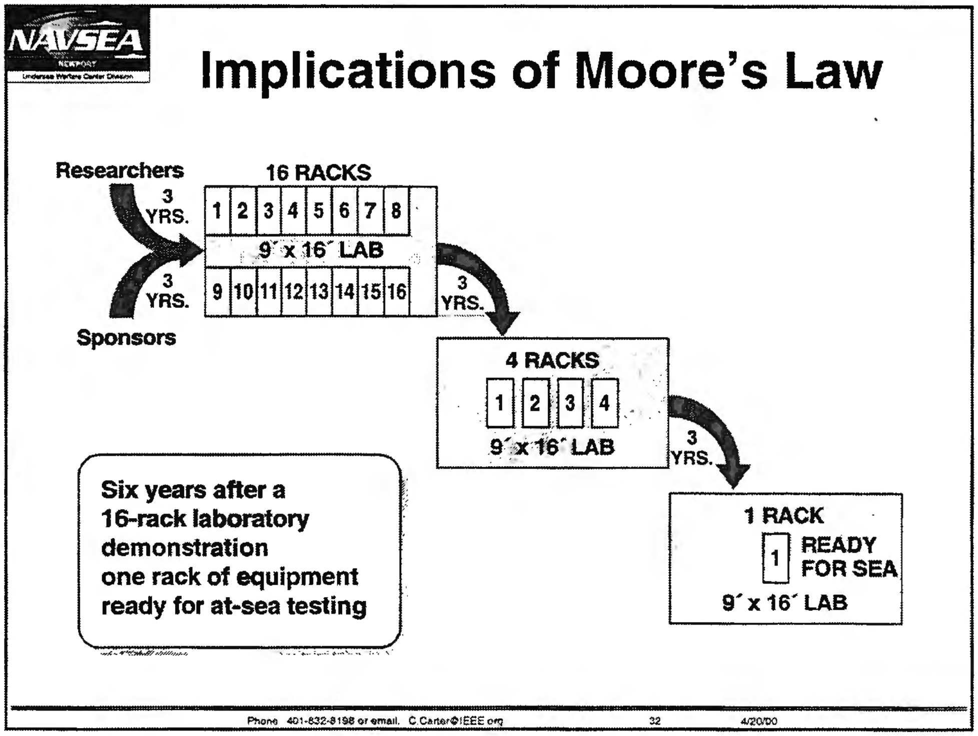

Implications of Moore's Law

Researchers

3 YRS.

3 YRS.

Sponsors

16 RACKS

1 2 3 4 5 6 7 8

9´ x 16´ LAB

9 10 11 12 13 14 15 16

3 YRS.

4 RACKS

1 2 3 4

9´ x 16´ LAB

3 YRS.

1 RACK

1 READY FOR SEA

9´ x 16´ LAB

Six years after a
16-rack laboratory
demonstration
one rack of equipment
ready for at-sea testing

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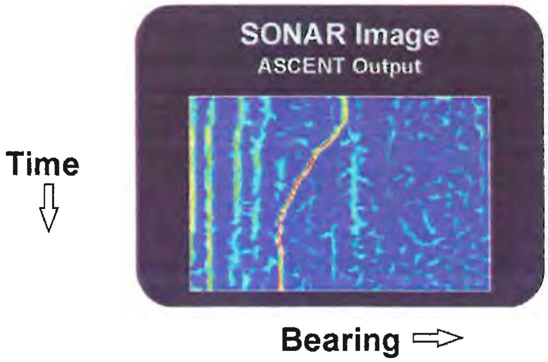
Notional FAST CNS BTR Display

Preliminary Results of Applying ASCENT Algorithm to Bearing-Time Recorder (BTR) Data



Results with Dr. Finkel, UPENN demonstrate full automation of visual display of acoustic data

- Modeled after the human visual processing system
- ASCENT extracts salient contours from a real BTR display

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Measuring Sonar Performance

SONAR FUNCTIONS	SONAR TEST METRICS (FUNCTIONS OF TIME AND SNR)
DETECTION / CLASSIFICATION	ROC, DEFLECTION d, RANGE ADVANTAGE, ARRAY GAIN, INITIAL DETECTION TIME, HOLDING TIME
LOCALIZATION (RANGE, BEARING, DEPTH)	BIAS, VARIANCE, $MSE = BIAS^2 + VAR$

RYJ 7056

The Sonar Equation

For passive sonar,

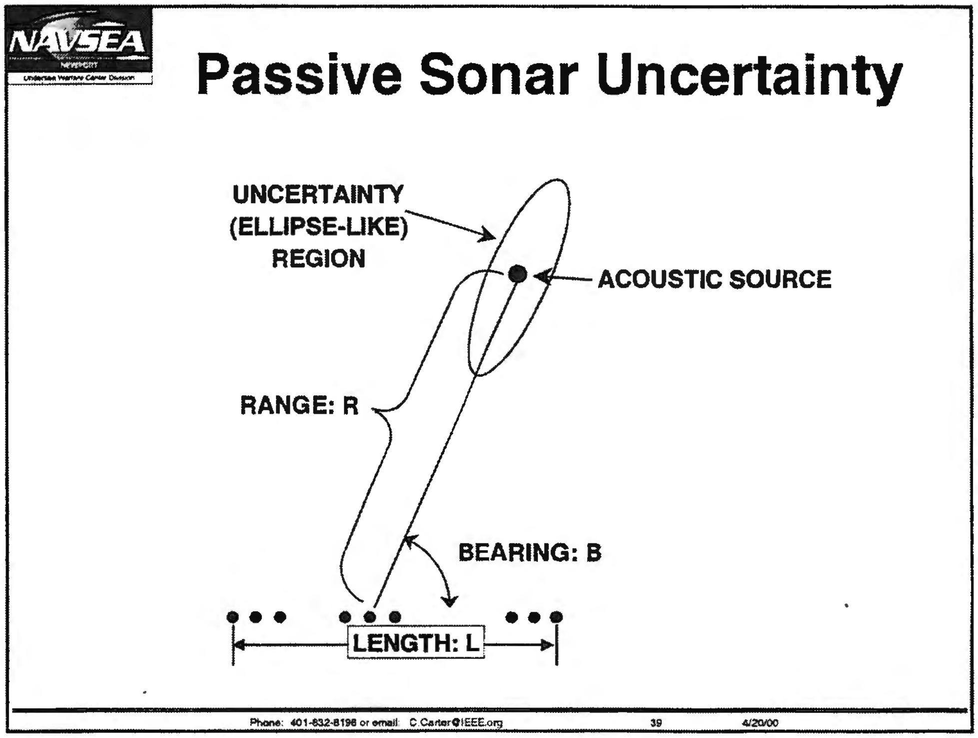
$$FOM_P = L_S - (L_N - N_{DI}) - N_{RD.}$$

For active sonar,

$$FOM_A = (L_S + N_{TS}) - (L_N - N_{DI}) - N_{RD}$$

Array Gain

- In the simplest case, the increase in SNR due to the beamformer, called the *array gain* (in dB), is given by
  - $10 \log_{10}$ (The Number of Sensors)
- More Generally it is
  - AG = SG - NG



Passive Sonar Uncertainty

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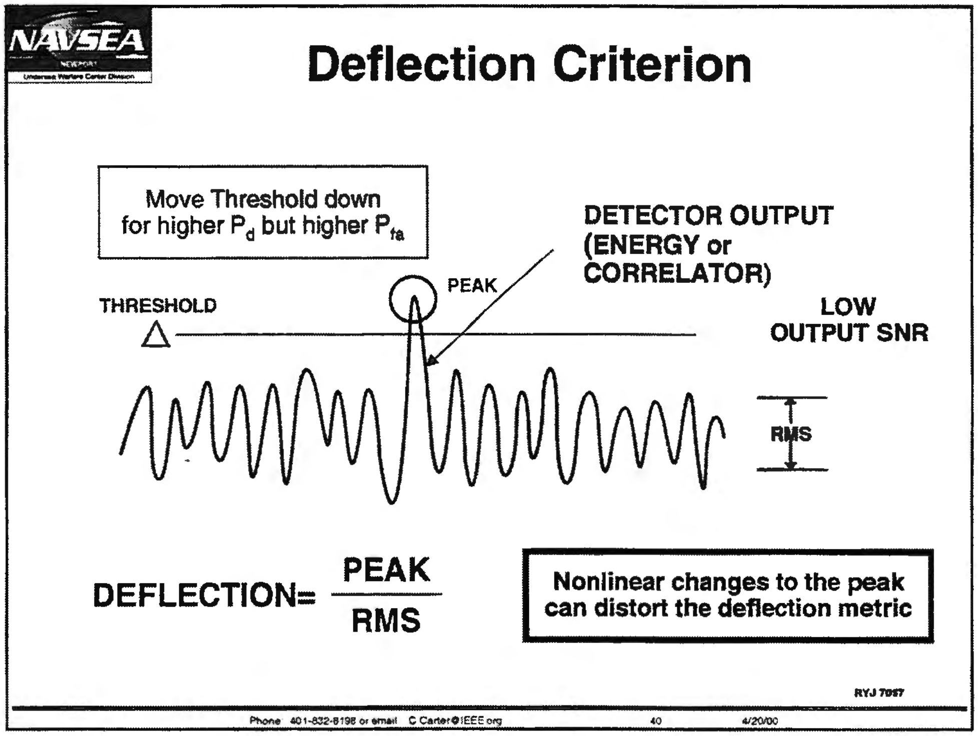

Deflection Criterion

Move Threshold down for higher P_d but higher P_{fa}

$$\text{DEFLECTION} = \frac{\text{PEAK}}{\text{RMS}}$$

Nonlinear changes to the peak can distort the deflection metric

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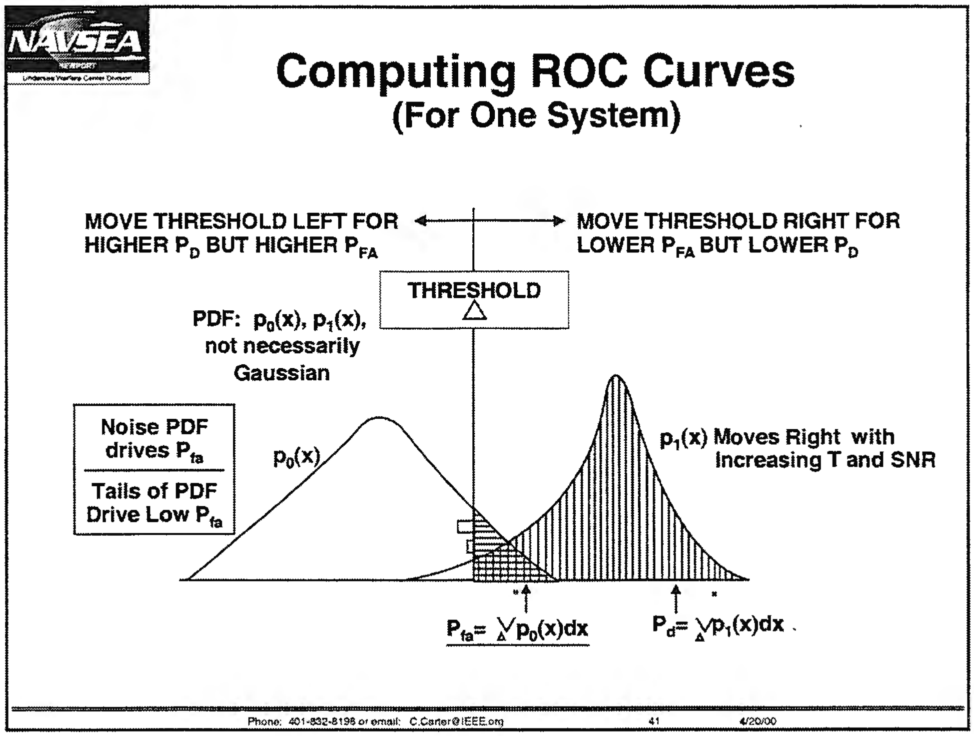


Computing ROC Curves

(For One System)

MOVE THRESHOLD LEFT FOR HIGHER P_D BUT HIGHER P_{FA}

MOVE THRESHOLD RIGHT FOR LOWER P_{FA} BUT LOWER P_D

THRESHOLD Δ

PDF: $p_0(x)$, $p_1(x)$, not necessarily Gaussian

Noise PDF drives P_{fa}

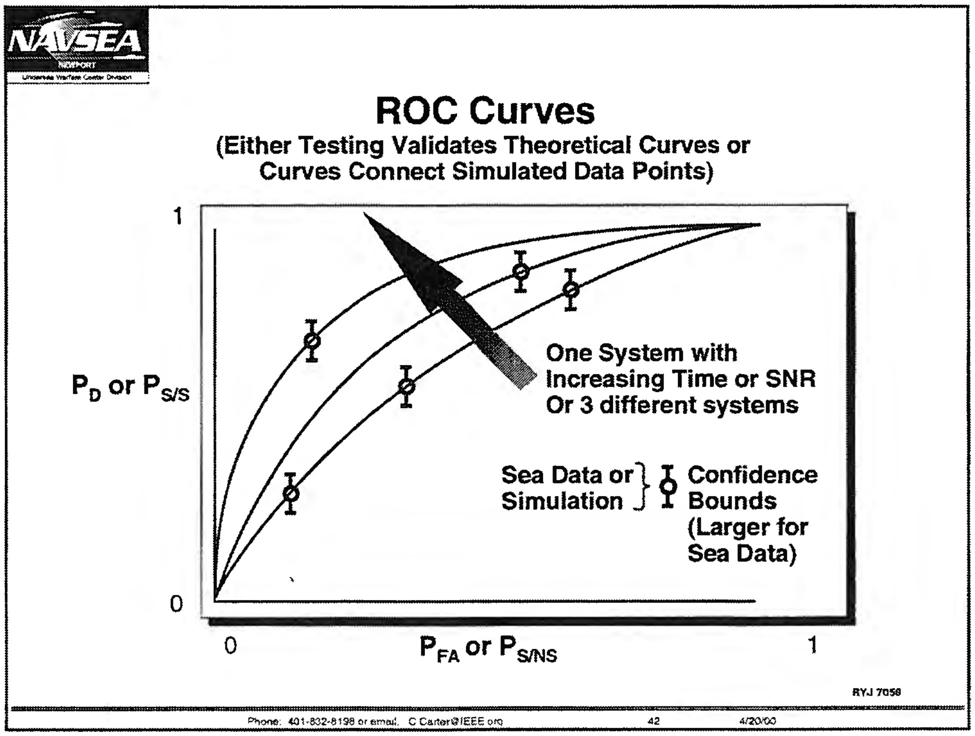
Tails of PDF Drive Low P_{fa}

$p_0(x)$

$p_1(x)$ Moves Right with Increasing T and SNR

$P_{fa} = \int_{\Delta}^{\infty} p_0(x)dx$

$P_d = \int_{\Delta}^{\infty} p_1(x)dx$



ROC Curves

(Either Testing Validates Theoretical Curves or Curves Connect Simulated Data Points)

One System with Increasing Time or SNR Or 3 different systems

Sea Data or Simulation } Confidence Bounds (Larger for Sea Data)

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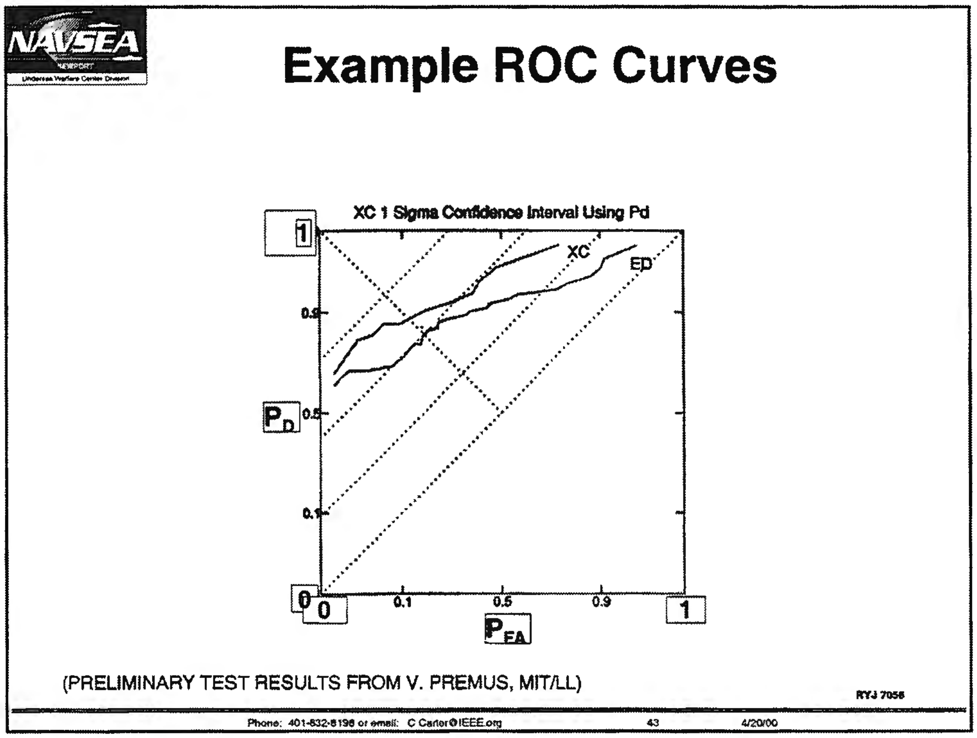

Example ROC Curves

(PRELIMINARY TEST RESULTS FROM V. PREMUS, MIT/LL)

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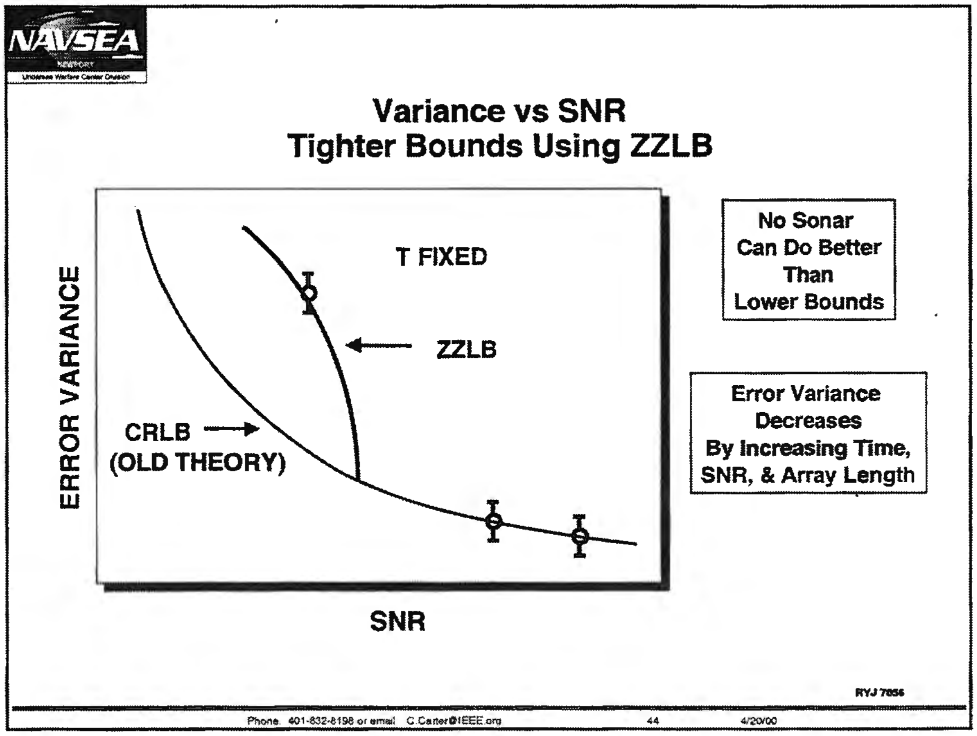

Variance vs SNR
Tighter Bounds Using ZZLB

No Sonar
Can Do Better
Than
Lower Bounds

Error Variance
Decreases
By Increasing Time,
SNR, & Array Length

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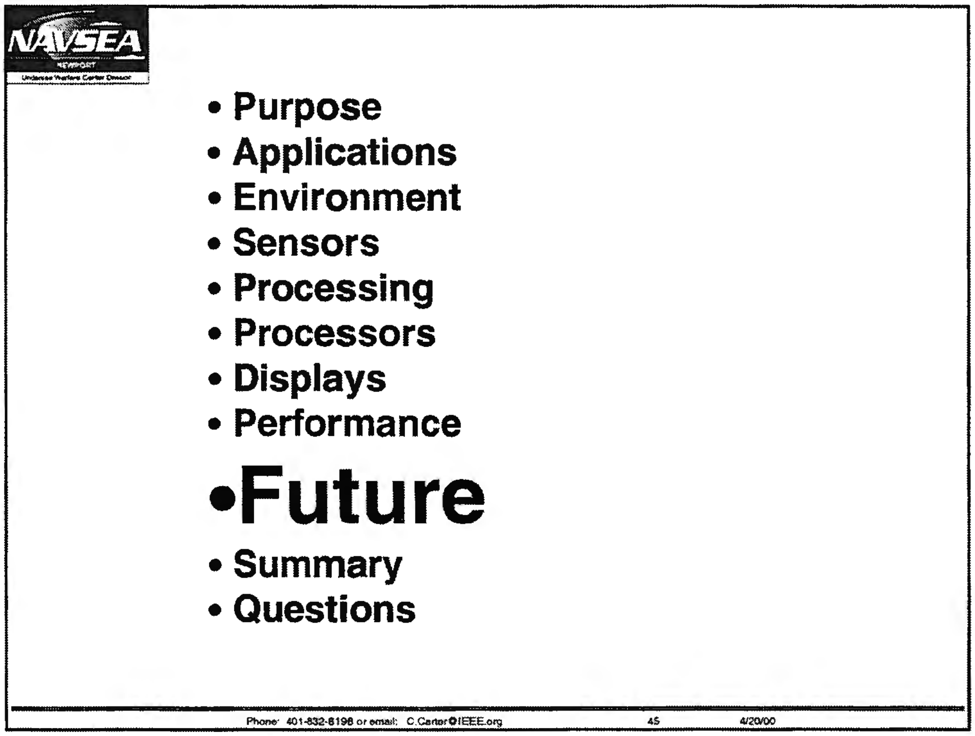

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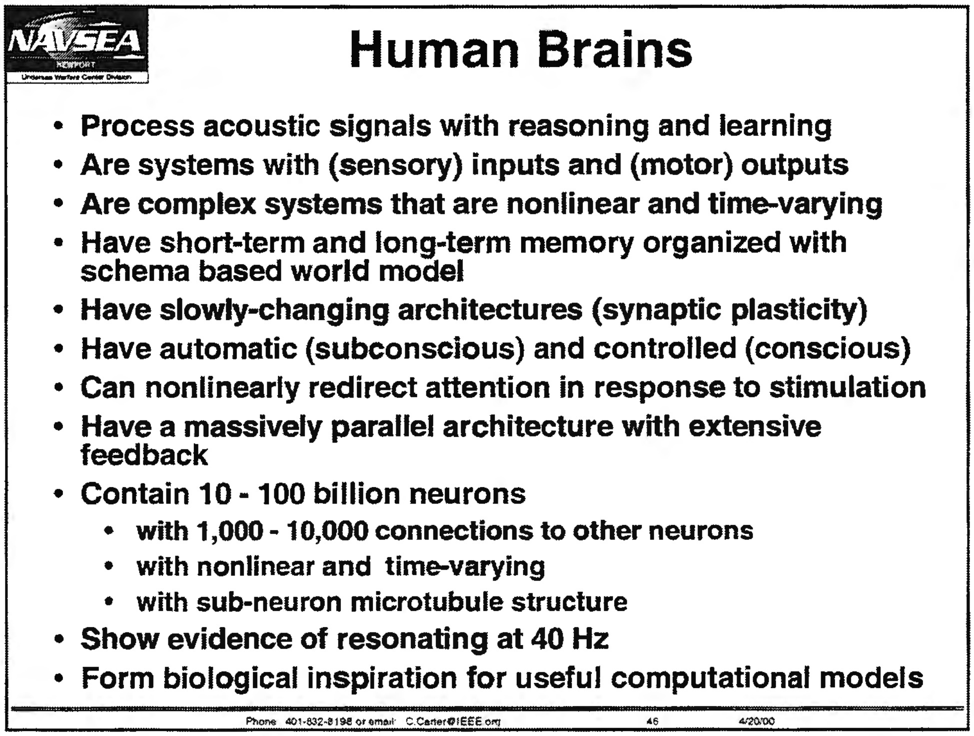

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Human Brains

- Process acoustic signals with reasoning and learning
- Are systems with (sensory) inputs and (motor) outputs
- Are complex systems that are nonlinear and time-varying
- Have short-term and long-term memory organized with schema based world model
- Have slowly-changing architectures (synaptic plasticity)
- Have automatic (subconscious) and controlled (conscious)
- Can nonlinearly redirect attention in response to stimulation
- Have a massively parallel architecture with extensive feedback
- Contain 10 - 100 billion neurons
  - with 1,000 - 10,000 connections to other neurons
  - with nonlinear and time-varying
  - with sub-neuron microtubule structure
- Show evidence of resonating at 40 Hz
- Form biological inspiration for useful computational models

Our Vision

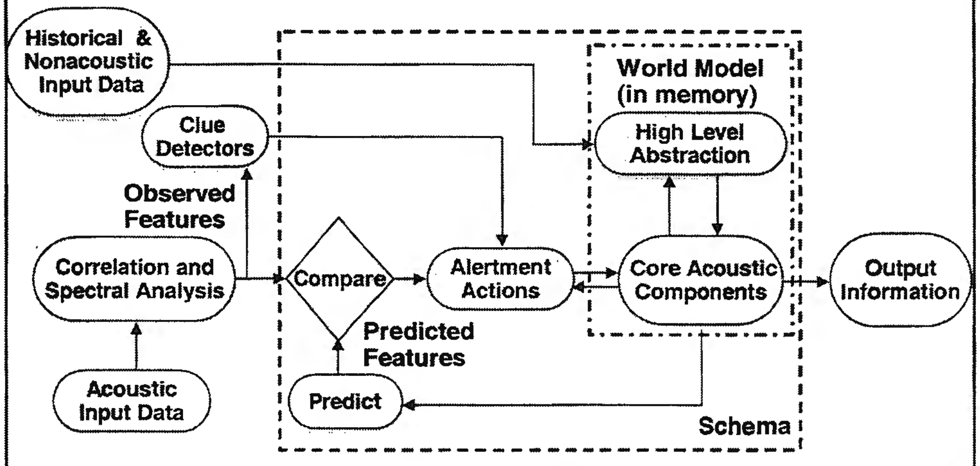
A Revolutionary

Fully Automated System Technology (FAST)

Cognitive Neuroscience (CNS) System that will:

- **Replace human operators with fully automated "silicon-based" assistants that recommend timely decisions with expert or "ace" abilities to a human machine supervisor**
- **Perform well in new acoustic environments**
- **Handle an order of magnitude more acoustic data**
- **Fuse, compress, & merge data into information**
- **Display needed information in the right format, to the right decision maker, at the right time**
- **Adapt to new tasks by learning & reasoning**

Prediction Driven Element of a CNS Sonar Architecture



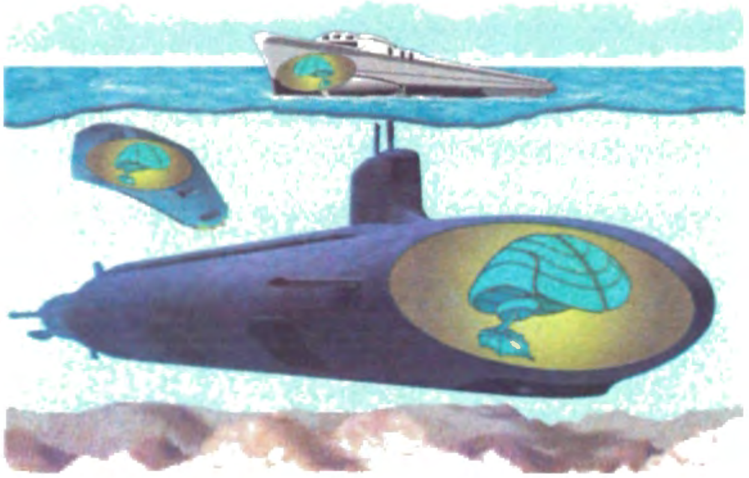
Note use of feedback, memory, alertment, and world model

Modified from Ellis, 1996 MIT Ph.D. Thesis

Open FAST CNS Questions

- How do we test & evaluate
  - a complex time-varying, nonlinear system?
  - learning, reasoning, and adaptability?
- What extensions are required to build a FAST CNS system?
- How to demonstrate a FAST CNS system?
- How does the internal architecture change with time?
- Is problem scalable? Is a CNS system demonstrable in small system? Or does it take a large system? How many neurons should be in the first phase test bed system system?
- What are appropriate architectures for our CNS system?
- How will we "program" our CNS system?
- How will our CNS system learn?
- How and at what data rates will we stimulate system?
- How does our CNS system implement the subconscious (automatic) and conscious (controlled) mind?

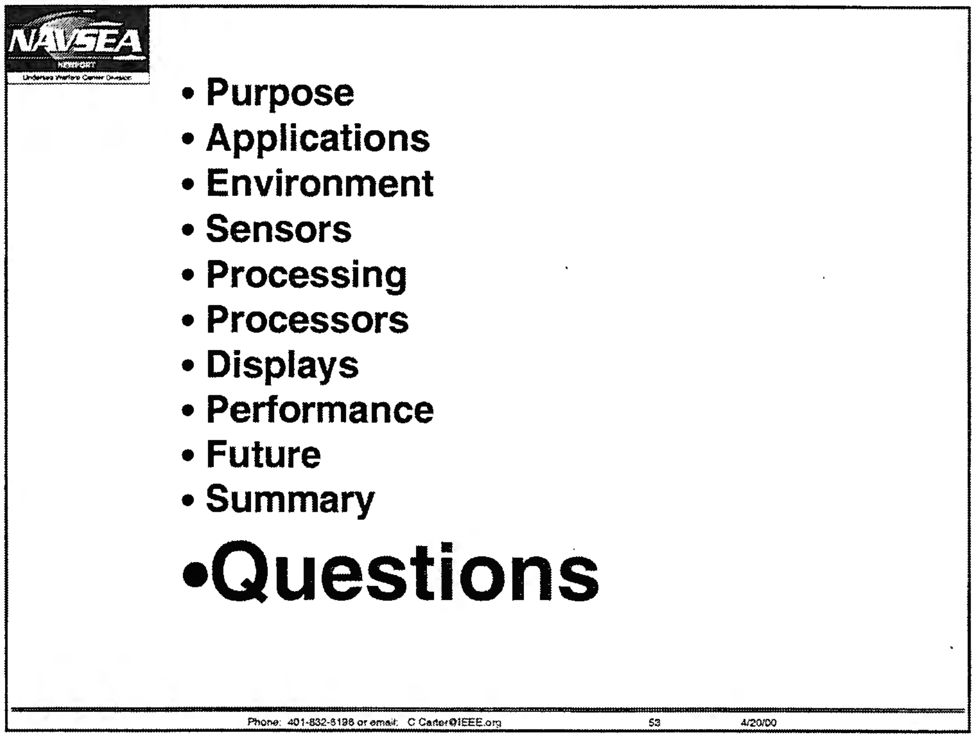
FAST CNS Sonar Systems



- Purpose
- Applications
- Environment
- Sensors
- Processing
- Processors
- Displays
- Performance
- Future
- **Summary**
- Questions

Summary

- Provided an overview including Fourier based Coherence and Time Delay Estimation signal processing methods and their performance
- Discussed a FAST CNS Future view
- Stimulated thoughts on dual-use application of Fourier based Coherence and Generalized Cross-Correlation Smoothed Coherence Transform to bio-medicine, commercial fishing, fish monitoring and treaty compliance



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- **Purpose**
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- **Summary**

•Questions

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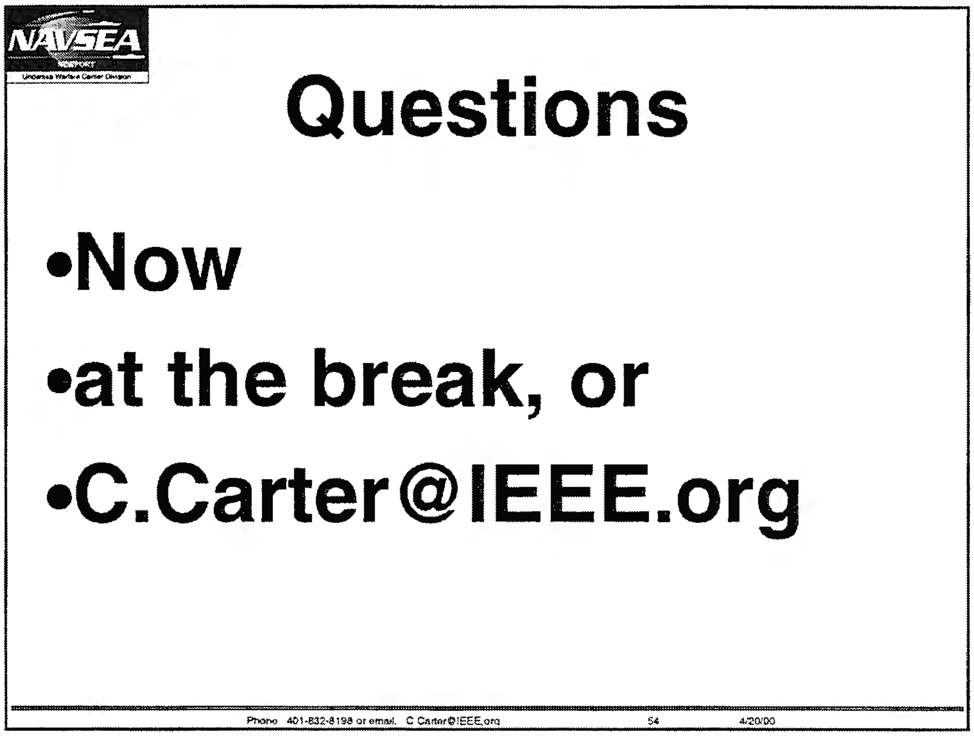

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Questions

•Now

•at the break, or

•C.Carter@IEEE.org

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