ISR Current Mapping Radars

i-Multi-Frequency HF Radar:

Mapping Current Shear and Vector Winds, Ship Target Classification and Tracking

ii - Microwave Radars for Nearshore Applications:

Currents, Wave Height and Offshore Bar Mapping

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Outline

- Company, Personnel Background
- Digital Transceiver Technology
- ONR Wind Mapping SBIR Using HF SWR
- Some Recent Results on Current shear Mapping
- Volume current estimate from Velocity Projection
- Ship Classification by RCS Spectroscopy
- Marine Radar Applications

Who We Are

- Imaging Science Research, Incorporated, A Virginia Small Business
  - Established April 2001
  - President: Dennis Trizna, Ph.D., NRL 31 year career in Radar & Remote Sensing Divisions
- Staff:
  - Jim Gordon, Digital Design Engineer
  - Stephan Schulz, Firmware Design Engineer
  - Phaneel Piratla, MS Electrical Engineering, digital control software
  - Lillian Xu, Ph.D. Electrical Engineering, Algorithms & Analysis
  - Rick Castles, BS Electrical Engineer, display software
  - Steven Le, Electrical Engineering Co-Op student
- Hardware Focus: *Digital Radar Transceiver system*
- Applications:
  - Multi-frequency, Bistatic HF Radar
  - Marine Radar for Coastal Process sensing
  - GPS scattering, remote sensing
  - Coherent L and C band radars for remote sensing processes

Background of Dennis Trizna

- 10 years of HF radar research, 1970-1981- Radar Division of NRL
  - FPS-95 OTH Soviet Union surveillance radar based in UK
    - Declassified in 90's in US,
    - Responsible for:
      - Surface Wave long range target tracking experiments
      - Ionospheric Heating experiments
      - Noise studies related to Clutter-Related-Noise problem
  - MADRE OTH radar at NRL
    - Ocean weather system mapping
    - Ship & Aircraft Tracking
  - San Clemente Island, NOAA/NRL multi-frequency HF radar
    - Navy Target / Sea Clutter studies
    - Multi-frequency HF radar RCS measurements of small boats
- 10 years of microwave radar studies at low grazing angles - Radar Division
- 11 years of marine radar studies of coastal processes
  - Radar & Remote Sensing Divisions
- 8 years of dual-hatted program management at ONR in Remote Sensing
- Retired from Government service April 2001, established ISR Inc

Unclassified Articles/Experience Relevant to HF radar

- **1971-1973, FPS-95 HF OTH Surveillance Radar, Orfordness, England**
- **Long, A.E. & D.B. Trizna, "*Mapping of North Atlantic winds by HF radar sea backscatter interpretation*", IEEE Trans. Ant. & Prop, AP-21, pp.. 680-685, 1973.**
  - **Conceived of se of Approach/Recede Bragg ratio to determine wave/wind direction in OTH mode**
  - **Alf Long was visiting scientist from UK who completed study started before FPS-95 program**
- **Ahearn, J.L, et al, "*Proceeding of the IEEE, 62, pp. 681-687*", June 1974.**
  - **Several examples of mapping of movement of storms through the Atlantic, while DBT in UK.**
- **Trizna, D.B., J.M. Headrick, R.W. Bogle, J.C. Moore, "*Directional sea spectrum determination using HF Doppler radar techniques",* IEEE Trans. Ant. & Prop, AP-25, pp. 4-11, 1977.**
  - **First peer-reviewed 2nd-Order Doppler sea scatter published model, using E.M. 2nd order effects only**
- **Trizna, D.B., J.M. Headrick, R.W. Bogle, J.C. Moore, "*Observation of the Phillips resonance mechanism for generation of wind waves",* JGR, 85, pp. 4946-56, 1980.**
  - **2-30 MHz SCI Radar 1st order Bragg line amplitudes vs azimuth, temporal development of wave spectrum**
- **Trizna, D.B., "*Mapping ocean currents using over-the-horizon radar*", International Journal of Remote Sensing, 3, pp. 295-301, 1982.**
  - **First time OTH radial current components used to locate major current field: the Gulf Stream**
- **Trizna, D.B., USPTO Patent #4,633,255, "*Method for sea surface high frequency radar cross-section estimation using Doppler spectral properties* ", 30 December 1986. (Directional Sea Spectrum Measure)**
- **Bogle, R.W & D.B. Trizna, "*Small boat HF radar cross sections*", NRL Memo Report 3322**
  - **Ship classification methodology**

FPS-95 Surveillance HF radar, Orfordness, Suffolk, UK

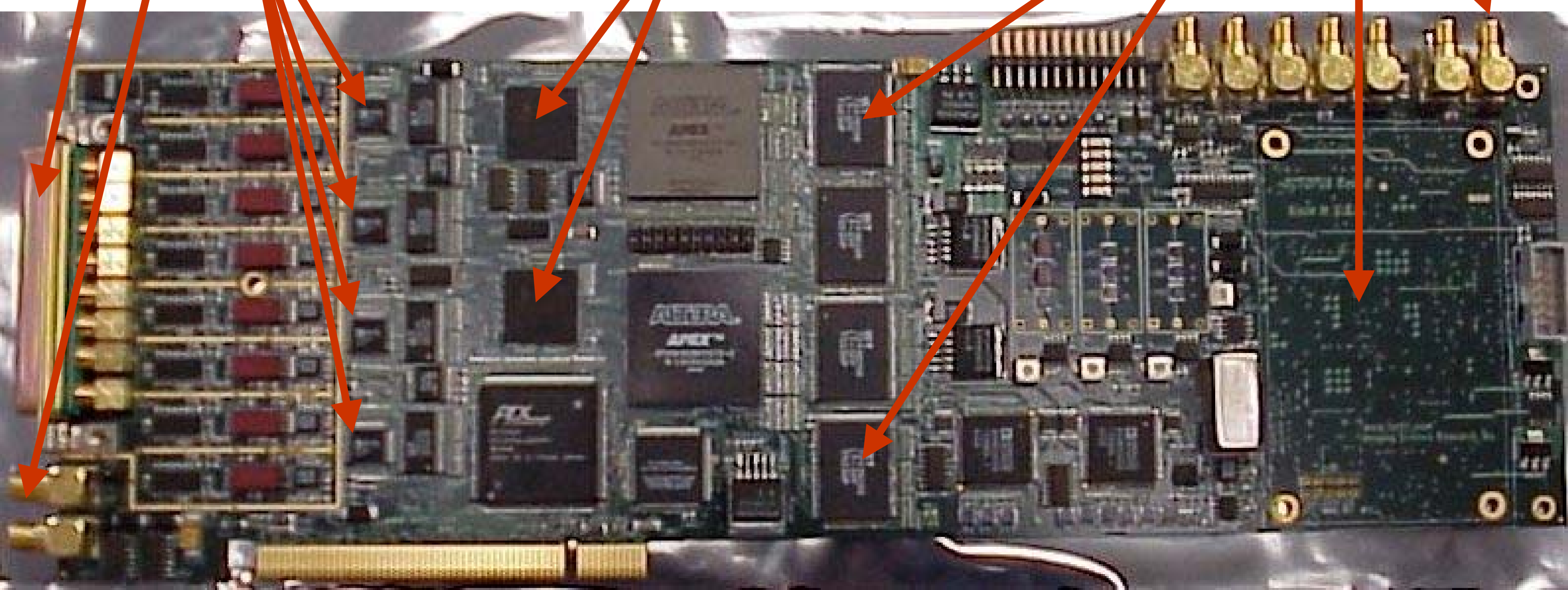
- 6 - 40 MHz frequency range
- 6 Megawatts transmit power, at 1-MW on each of 6 adjacent LP arrays
- Skywave coverage over eastern Europe, Soviet Union
- Surface wave coverage of the North Sea

Digital Transceiver Technology

- Developed under ONR contract
- Capable of use from HF through microwave
- Cell phone technology ported to radar design
- Transmit/Receive capability integrated to single PCI computer card
- Dedicated receiver computer under Linux

Octopus : Low Cost, 8-channel Digital Radar Transceiver

- Variety of output test signals available from Top Auxiliary SMA/Bracket
  - Pulse Envelope, DSS output direct & mixed, receiver blanking pulse, trigger, GPS 1-PPS
- 8 antenna inputs to 8 100-MHz A/D converters
- SMA connector pair for clock & trigger input/output
- Four 2-Channel A/Ds, two Digital Down Converters for RF filtering, FIFO Memory, GPS receiver



Features of the Octopus Radar Transceiver PCI Card

- **Programmable waveform generation**
  - coupled DDS pair for (1) waveform and (2) coherent A/D clock generation
  - Programmable Frequency set & pulse envelope with onboard mixer for spectrum control
    - 32 frequencies used in Navy RCS application
  - Variety of wave forms:
    - Simple Pulse - envelope programmable (all waveforms)
    - FM Chirp (Codar-like) or FM CW (WERA-like) pulse compression capable
    - Phase Code pulse compression capable
    - Random Noise - Repeated Code pulse-to-pulse for FIFO averaging, or Variable Code
- **8-channel 100- MHz A/D receive capability per card (capable of up to 4 cards, 32 antennas)**
- **FPGA Pair for housekeeping & real-time processing (2 pair of 4 parallel channels)**
- **Direct Digital Down conversion Pair for programmable digital filtering**
  - 8 A/D bits Real in, 16 or 32 bits I/Q out - Increases sampled dynamic range by ratio of SR/DDC-BW
- **FIFO memory pair for averaging digitized waveforms**
  - additional increase in dynamic range and reduction in recording volume, to PRF desired -32 bit output
- **DMA transfer to PC memory currently for storage**
- **Onboard GPS receiver Time for Temp-Corrected Oscillator or external ISR Rubidium Clock**
  - *Separate ISR Exciter card option for bistatic multi-site operation*, interleaved pulse ops on GPS time
  - *New 4 channel Receiver card* in development for Marine Radar Applications

ISR Navy SBIR Phase-1 contract :

- **Define a multi-frequency HF radar for mapping vertical ocean current shear and vector winds at km scales**

Objectives:

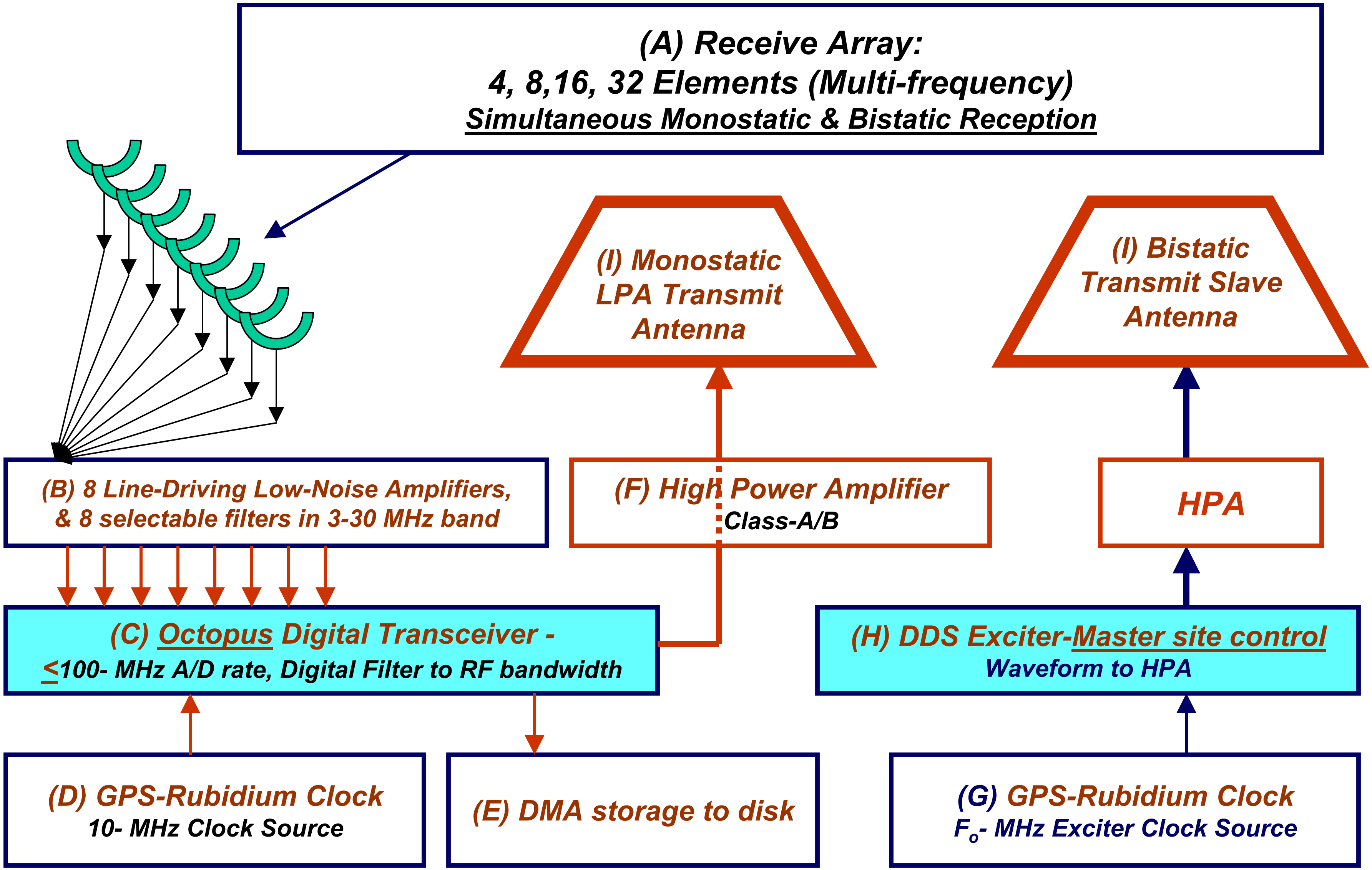
- ***Define Technology*** **required for multi-frequency HF radar**
  - **Bistatic capable - lower site costs, all processing centralized**
  - **Wide-band transmit antenna, 3-30 MHz potential**
  - **Incorporate state of the art digital transceiver technology**
    - **developed under second ONR program**
    - **Interleaved frequency operation, pulse-to-pulse switching**
- ***Measure current shear*** **using multi-frequency HF Radar**
- ***Infer wind speed estimate*** **from corresponding wind shear measure**

Technology Background:

The radar development is based on fully digital HF transceiver built on a PC card funded by ONR:

- **Windows-like operating environment**
- **Digitally programmed transmit waveform - to Hi Power Amp**
  - **Pulse-to-pulse frequency stepping for simultaneous frequency scan**
- **8 receive channels, 16 or 32 bit word capable**
  - **Prime Mapping Radar: 4-element receive array with DOA processing**
  - **WERA-like FM-CW system, but with multiple frequencies**
    - **Use Loop receive elements to null out transmitted signal via direct path**
- **Bistatic system provides vectors with *all processing at single site***
  - **Communications between sites minimal**
  - **GPS time pulse-synchronization for bistatic operation**
- **Rubidium Clock Option for low phase noise - ship tracking**
  - **Existing systems will not detect small vessels without such capability**

ISR Multi-static Radar-1 processing site

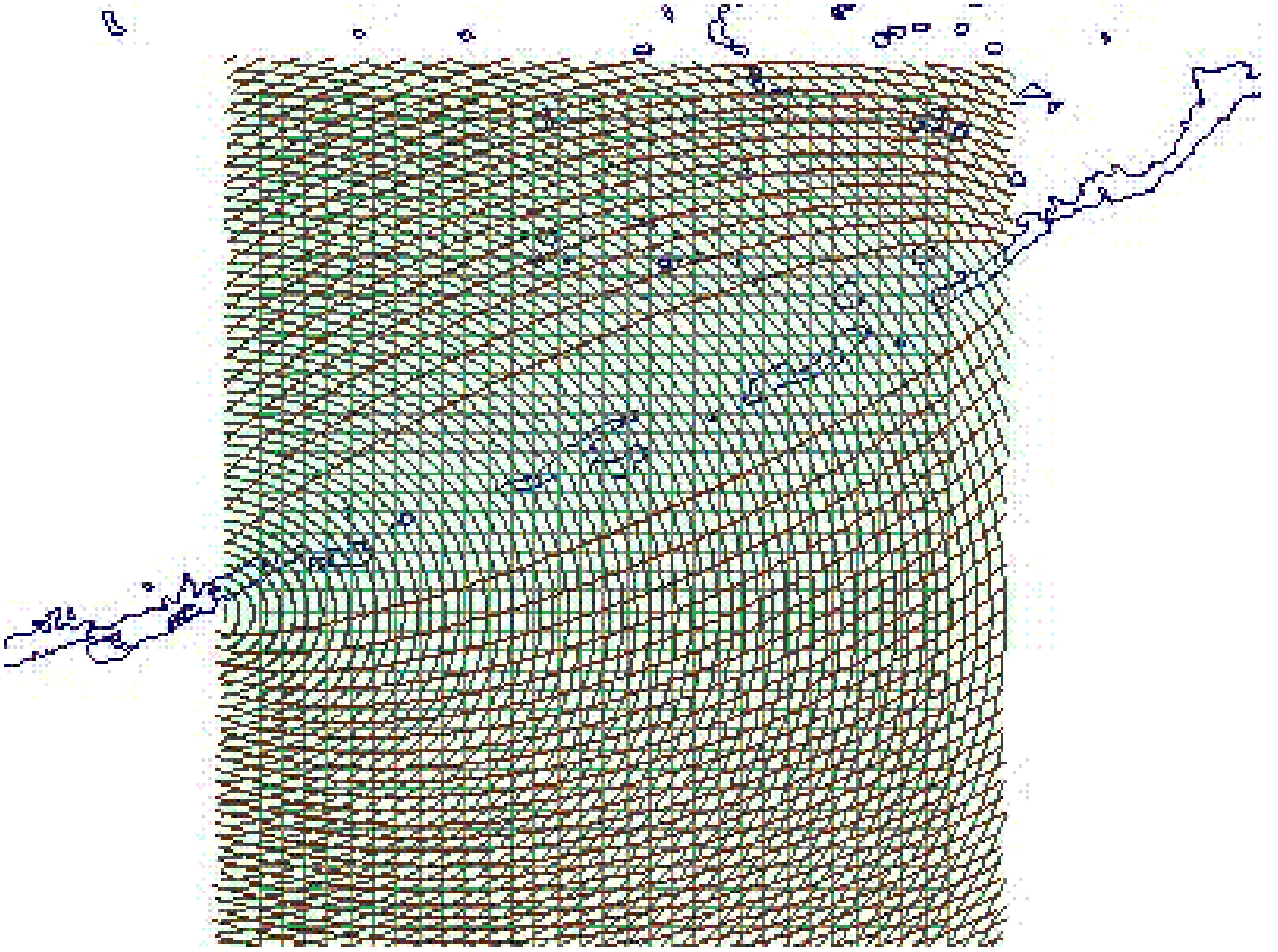


Bistatic/Monostatic Coverage

2-Site Bistatic Coverage Example:

Florida Keys, 1-km Pulse,variable bistatic spatial resolution

Currents are mapped at each 0.1-deg. lat/lon, interpolated from range-azimuth data



Define Technology

Radar Issues addressed during ONR Phase-1 SBIR

- A. Multi-frequency Transmit Antenna developed (3-60 MHz)
  - Log Periodic Monopole Array built
  - Proprietary element design to achieve very low frequencies with short elements
- B. Tunable High Power Amplifier (HPA) prototype built
  - ISR design, controllable with Octopus transceiver
  - Commercial HPA's have different external control methods-define in house
- C. Current measurement using a Small 4-Element Receive Array
  - Direction-of-Arrival (DOA) processing using 4 Elements
  - ISR Hire, recent GMU Ph.D. grad under Prof. Harry Van Trees

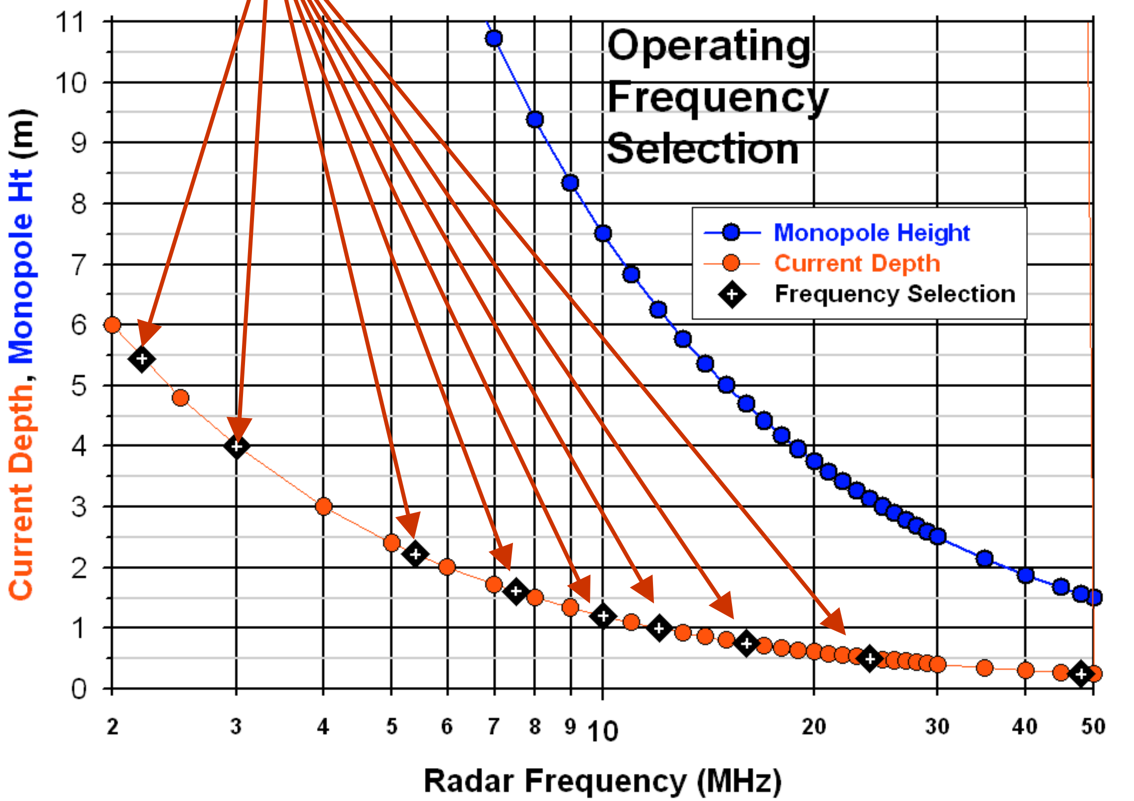
Define Technology - A

Broadband Transmit Antenna requirement, using a single HPA driven by Vertical Current Shear Measurement requirement:

Desired depth defines transmit antenna size - unrealistic at 3 MHz

- Currents measured represent average over ~4% of Radar wavelength
- Multiple frequencies probe deeper, providing depth dependence, shear
- 5-10 frequencies desirable over full HF band

Extreme height of λ/4 monopole at desired low frequencies creates problems of deployment, maintenance, as well as environmental impact



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Solution: Log Periodic Array for continuous frequency coverage over 3-30 MHz

- **LPA Features:**
  - Monopole elements at high frequencies, but height increases with longer wavelengths
  - Switch to Proprietary design element for <15.4 MHz, 3-m fixed height
  - Single feed line connecting all elements, RF balun for impedance matching
- **Allows for single HPA, no need for switching between frequencies**
  - If space - limited could use 4-frequency, 2/4-monopole antenna, 4 HPA's & low power switching

Define Technology - B

High Power Amplifier solution - develop our own unit:

- Maintain full control of hardware with Octopus control bus signals
  - Control signals vary between manufacturers, allows us to set standard spec relative to Octopus
- Multiple units triggered on alternating pulses, switching done at low level
  - GPS time synchronous-tested, use in bistatic applications
  - Single unit sufficient for LPA antenna, continuous frequency capability 3-50 MHz
- Prototype developed using COTS HF components
  - 600 kWatt CW output possible
  - can be Frequency Modulated for pulse compression (as WERA FM-CW or CODAR FM-Chirp)
- Rack - mount Prototype below
  - has temporary temperature and current sensors for monitoring
  - will be integrated into final system, digitally monitored by transceiver

Define Technology - C

Small Receive Array for Current Mapping - DOA processing for 4 elements

- **Market demands minimal-area system**
  - **Coastal space at a premium**
- **Short arrays of few elements are required**
  - **Beam forming approach thus are not feasible**
- **DOA algorithms necessary to derive radial currents**
  - **Allows 3-6 element solution**

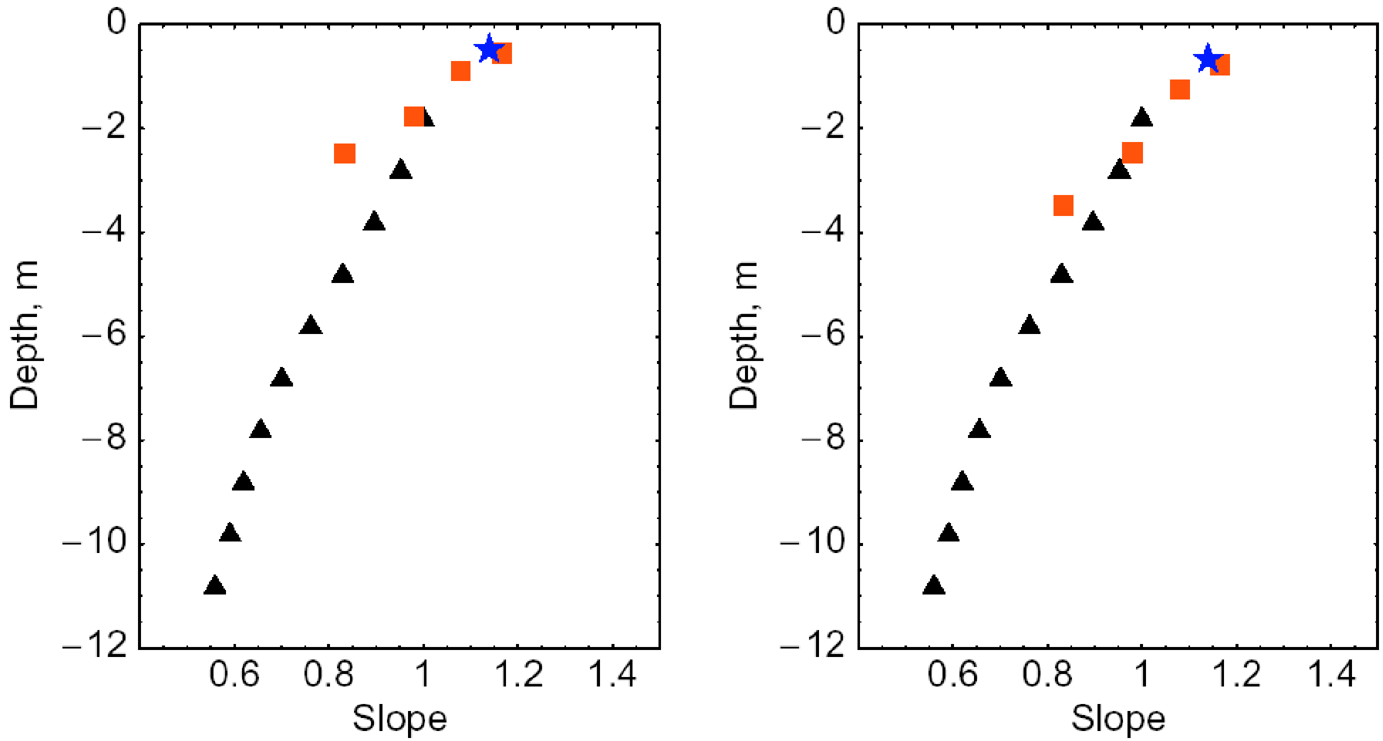
Some Recent Results

- Data collected at West Coast SPAWAR site
- Navy Ship RCS tests
- 32 frequencies, prototype pre-Octopus acquisition system
- 4 element Loop array, as with SBIR prototype

U Mich. Measurement of Current Shear

Vesecky, et al, HF current shear vs. ADCP (IGARSS 2001)

- **Currents measured at 4 radar frequencies (Red Squares)**
  - **Red squares represent radar measurement *1-km spatial average***
- **Acoustic Doppler Profiler (Black Diamonds)**
  - ***point measure* of current shear compares well with 1-km spatial radar average**

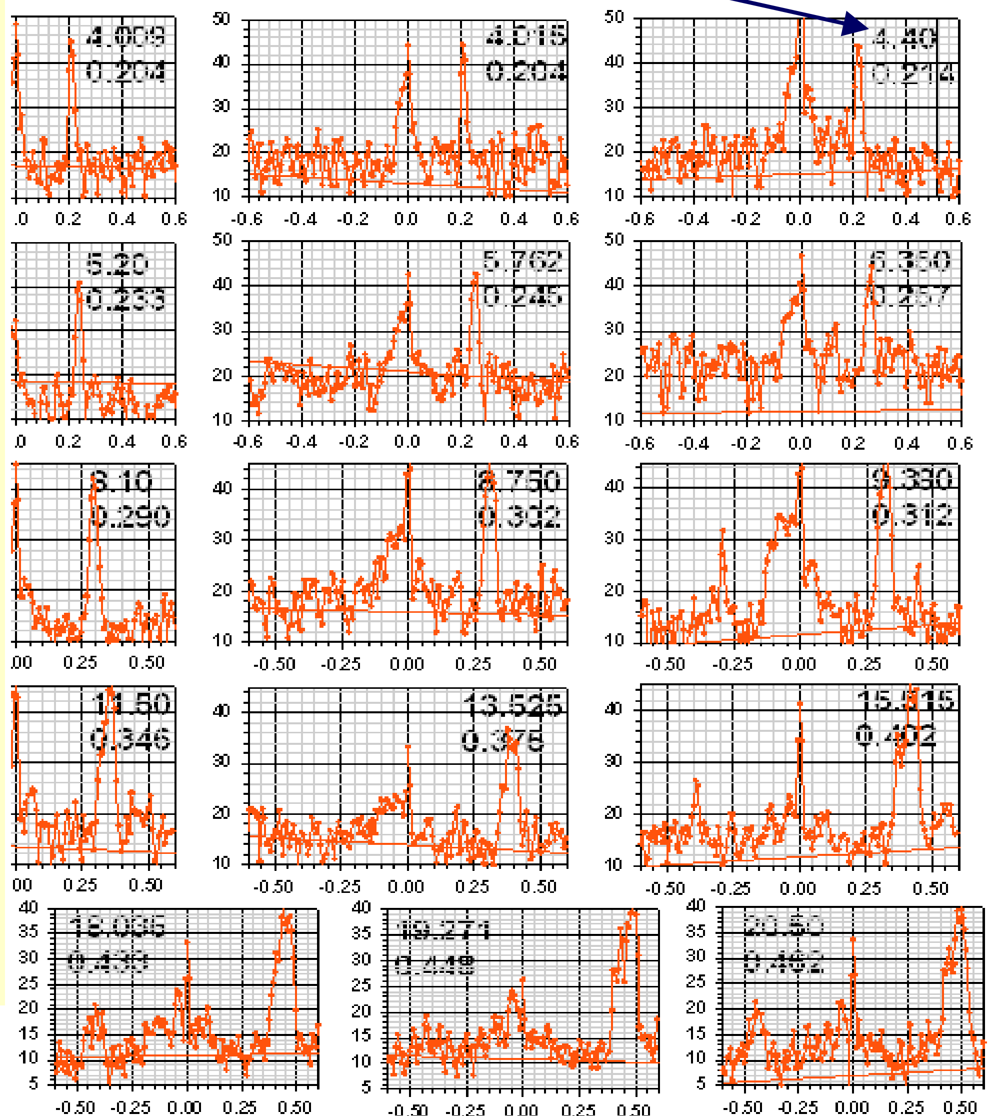


ISR Radial-Current Shear Measurement

Multi-frequency Doppler Spectra from SPAWAR August '03 Experiment

(Radar Frequency (MHz), expected Bragg line shift (Hz) indicated for each plot)

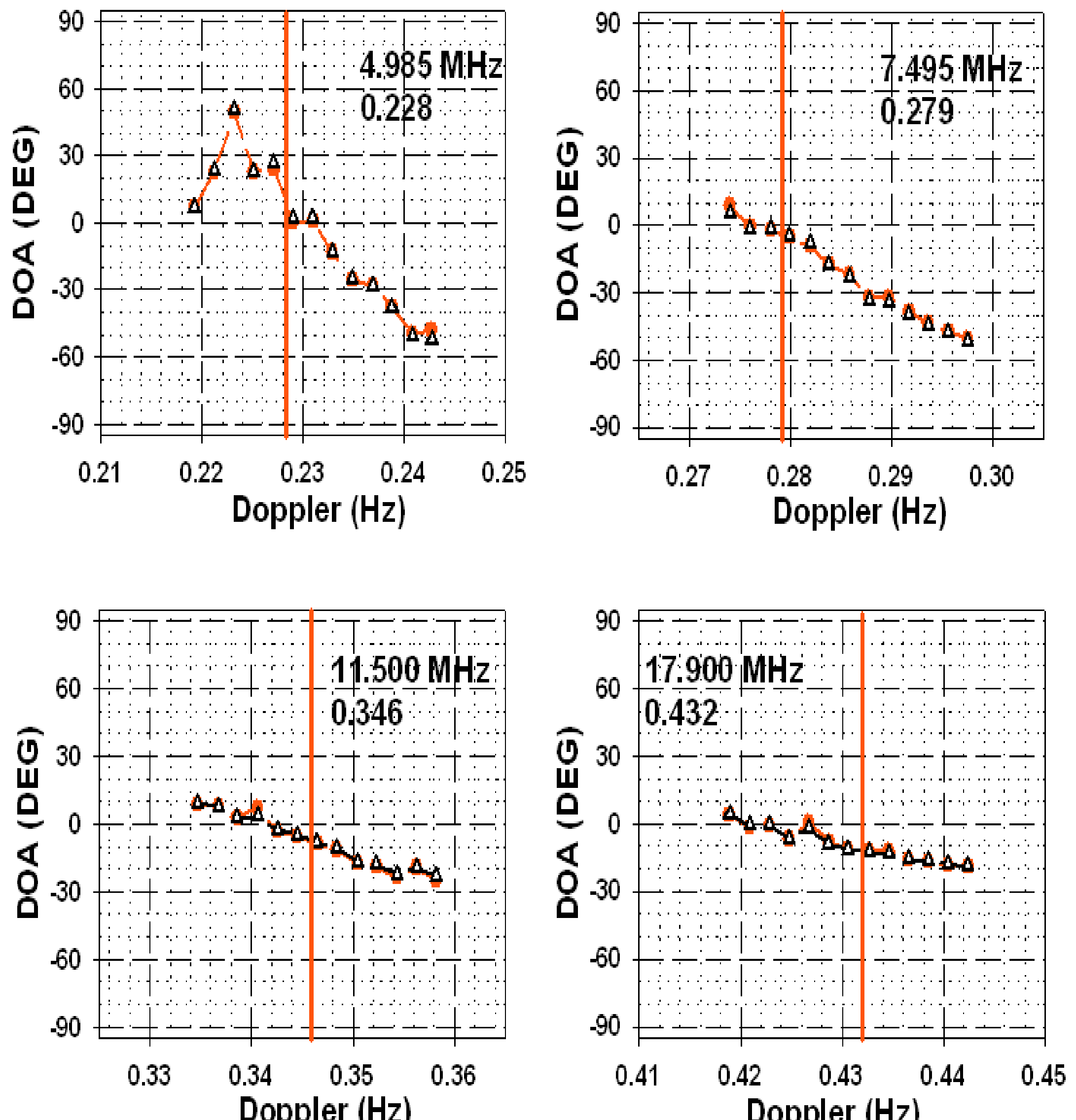
- **Radar Setup:**
  - 32 Frequencies using ISR prototype receiver
  - 4 kW SPAWAR HPA, ISR Exciter
  - Monocone 3-30 MHz Transmit antenna
  - 4-element receive loop array
- **15 of 32 spectra shown**
  - Broadened, but minimally shifted spectra indicate along-shore cross current
  - Change with radar frequency indicates current varies with depth - shear present.
- **Can we derive radial currents from such 4-antenna data using DOA Methods?**
  - Compare phase difference between 4 antenna elements for each Doppler spectral filter encompassing the broad Bragg line
  - The frequency spacing from the predicted filter is a measure of radial velocity for the direction determined from phase comparisons



Currents from DOA ISR Analysis

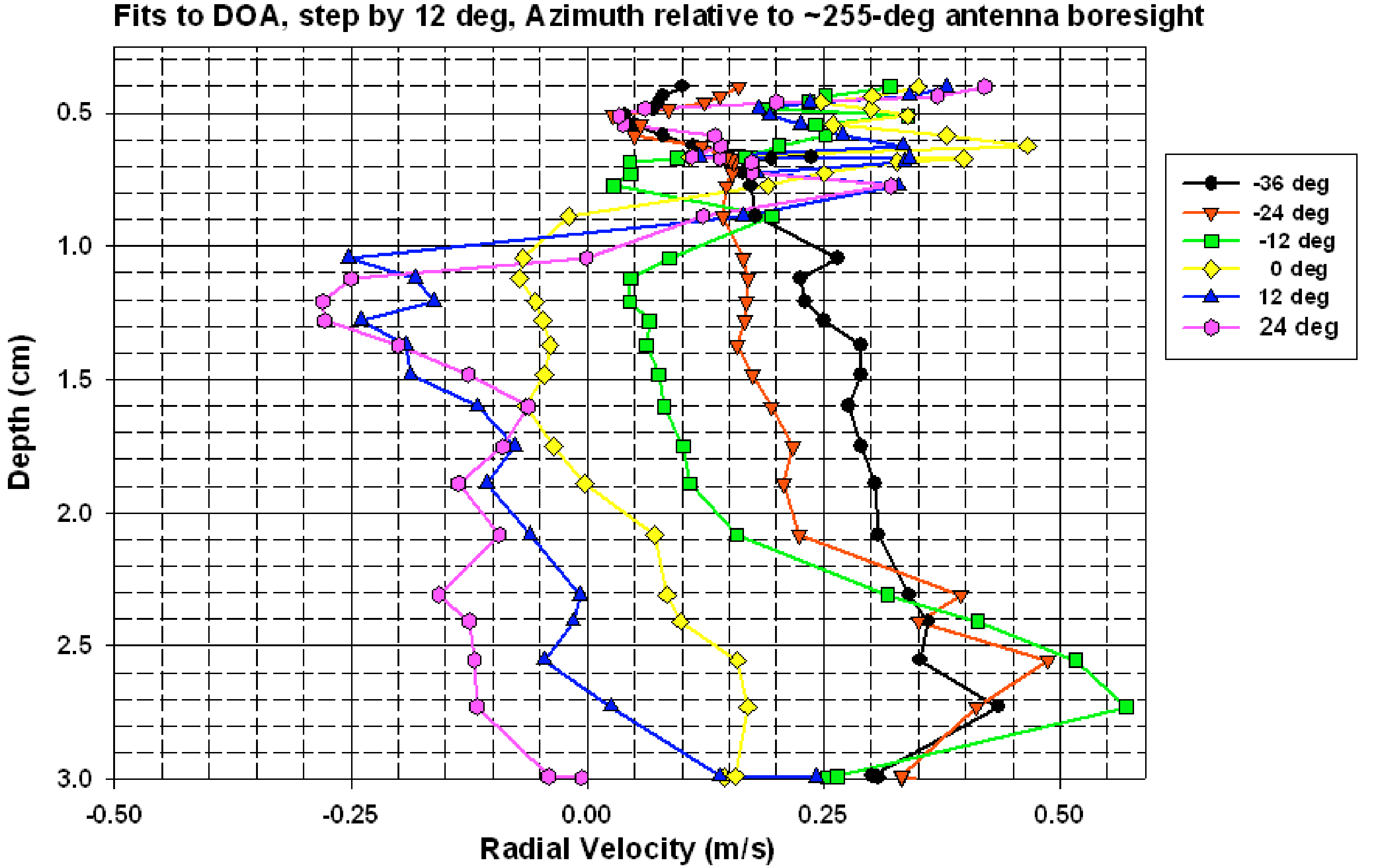
DOA algorithm used to derive radial currents.

- **Developed by ISR, Dr. Lillian Xu**
- **Tested first on dedicated target boat outbound along bore-site**
- **Trend of results in agreement with expected behavior due to crossing current along coast**
- **Red line indicates expected Bragg shift in Hz, spread about it indicates radial component of an along-shore current**
- **RESULT: Radial current Vs azimuth**



ISR Measure of Current Shear

- West Coast Ship RCS Experiment Data - very preliminary analysis
  - DOA Analysis of 4-element array, 4 data files covering 1 hr in time, 32 frequencies used 3-30 MHz
  - results for 6 bearings 12 deg apart, ~4 km offshore of SPAWAR RF site from ship track experiment
- Profile indicates transition from *wind driven shear* near surface to *eddy below 1 m*



Current Shear maps => Wind Speed maps

Ocean Current Coupling to the Atmosphere

- **Both atmosphere and water horizontal velocity profiles (winds and currents) satisfy *log profile* according to MO theory=>**
- ***u*(z) is wind friction velocity in atmosphere, $u_a(z)$ current velocity in water, $u_W(d)$**
- ***Assume that all current shear is induced by wind* and independent of bottom effects and other flows (e.g., Gulf Stream)**
- **Stress is constant across the water interface, so velocities at the surface behave as: $u_a(0)\rho_a = u_w(0)\,\rho_w$**
- **Wind speed can thus be estimated by inversion of stress continuity equation, referenced to standard 10-m height.**

$$u(z) = \frac{u_*}{k}\left[\ln\left(z/z_0\right) - \psi\left(z/L\right)\right]$$

where

u_* is the friction velocity

k is the von Karman constant 0.4

z_0 is the roughness length

L is the Monin - Obukhov length

$$L = \frac{T_0}{kg} \cdot \frac{c_p u_*^3}{H_0}$$

where

T_0 is the surface absolute temperature

H_0 is the surface heat flux

c_p is the heat capacity of air at constant pressure

u_* is the friction velocity

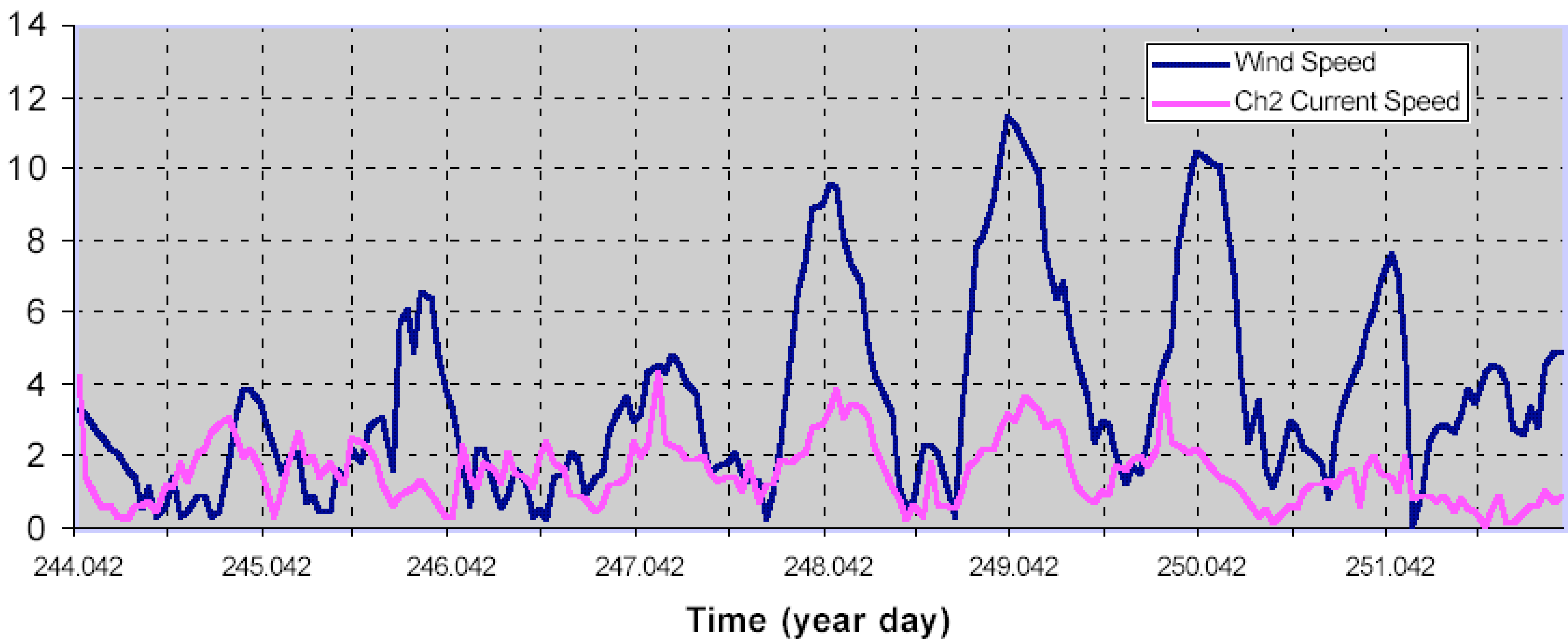
k is the von Karman constant 0.4

g is the acceleration due to gravity

Winds from Current Shear

Vesecky, et al, (IGARSS 02) Wind-Current Correlation

- HF radar observations of buoy winds and HF current speeds at 6.8 MHz
- Correlation are strong for sea-breeze conditions when the currents can be expected to be dominated by air-sea interaction
- At IGARSS ‘03, this group reported current shear observations and deduced wind speeds and compared with buoy winds to validate MO predictions discussed previously



Summary, Phase-1 SBIR

- Technology for multi-frequency current shear measure outlined, designed, built
  - Log-periodic monopole transmit array (LPMA) for testing, ship classification potential
    - Allows any frequency choice in 3-50 MHz band
    - ~ 60 ft long, may not satisfy some users' spatial constraints
    - Multiple resonant monopole choice an option for 4-5 frequency operation for commercial systems
  - Class A/B High Power Amplifier designed, prototype built and being used
    - Pair may be required to cover 3.5-30 MHz in tow steps due to 2nd harmonic nature of Class A/B
  - DOA algorithms developed, tested on West Coast data using identical receive array
    - Root MUSIC algorithm chosen for simplicity and speed of calculation
  - Deployed full HF radar at FRF, tested LPMA, HPA, exciter card
    - Fully transportable radar van, Chesapeake Bay mouth tests Spring '04 for ONR31
- Current shear/Wind Map measurements to begin Summer '04 at FRF site
  - Transceiver software due to be completed, Linux on stand-alone receiver platform
  - Bistatic site to be defined, transmitter deployed

Velocity Projection - Estimates of Shear from the surface to the bottom

- Shen and Evans have developed a methodology in which the momentum balance is estimated over the water volume from the surface to the bottom,
- It is based on a linearization of the balance equations, assigning boundary conditions in which near surface shear time series is an input
- It requires time series measurements at a cell and at adjacent cells in the X and Y directions.
- Two papers have been published on the subject:
  - Shen, C.Y. and T.E Evans, *Dynamically constrained projection for subsurface current velocity,* JGR, 107, pp. 24-1 to 24-13, 2002.
  - Shen, C.Y. and T.E Evans, *Surface to Sub-surface velocity projection for shallow water currents,* JGR, 106, pp. 6973 - 6984, 2001.
- A third has applied the method to estimate sea surface height variation from HF Doppler current measurements:
  - Marmarino, G.O., et al, Continental Shelf Research, 20, pp. 353-374, 2004.

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Velocity Projection

- Projection results from 2nd paper by Shen & Evans:
  - Sensitivity to time steps, scales
  - Modeled data, method applied
  - Viscous & inertial processes comparable in strength
- Variable eddy viscosity effects studied
- Earlier paper used OSCR radar data and ADCP in situ comparisons
- Method appears to be promising application of multi-frequency radar shear measurement <u>to provide current maps over the whole water column.</u>

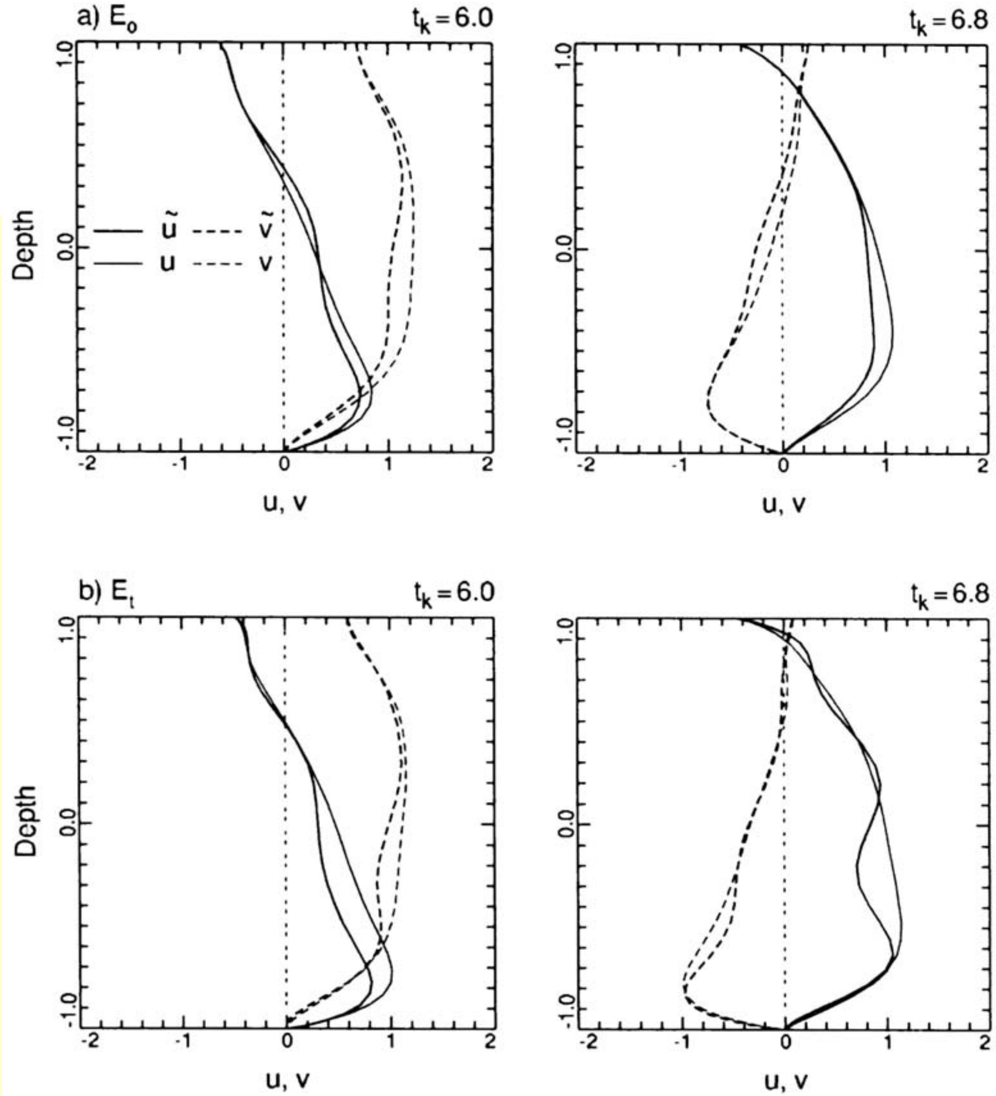


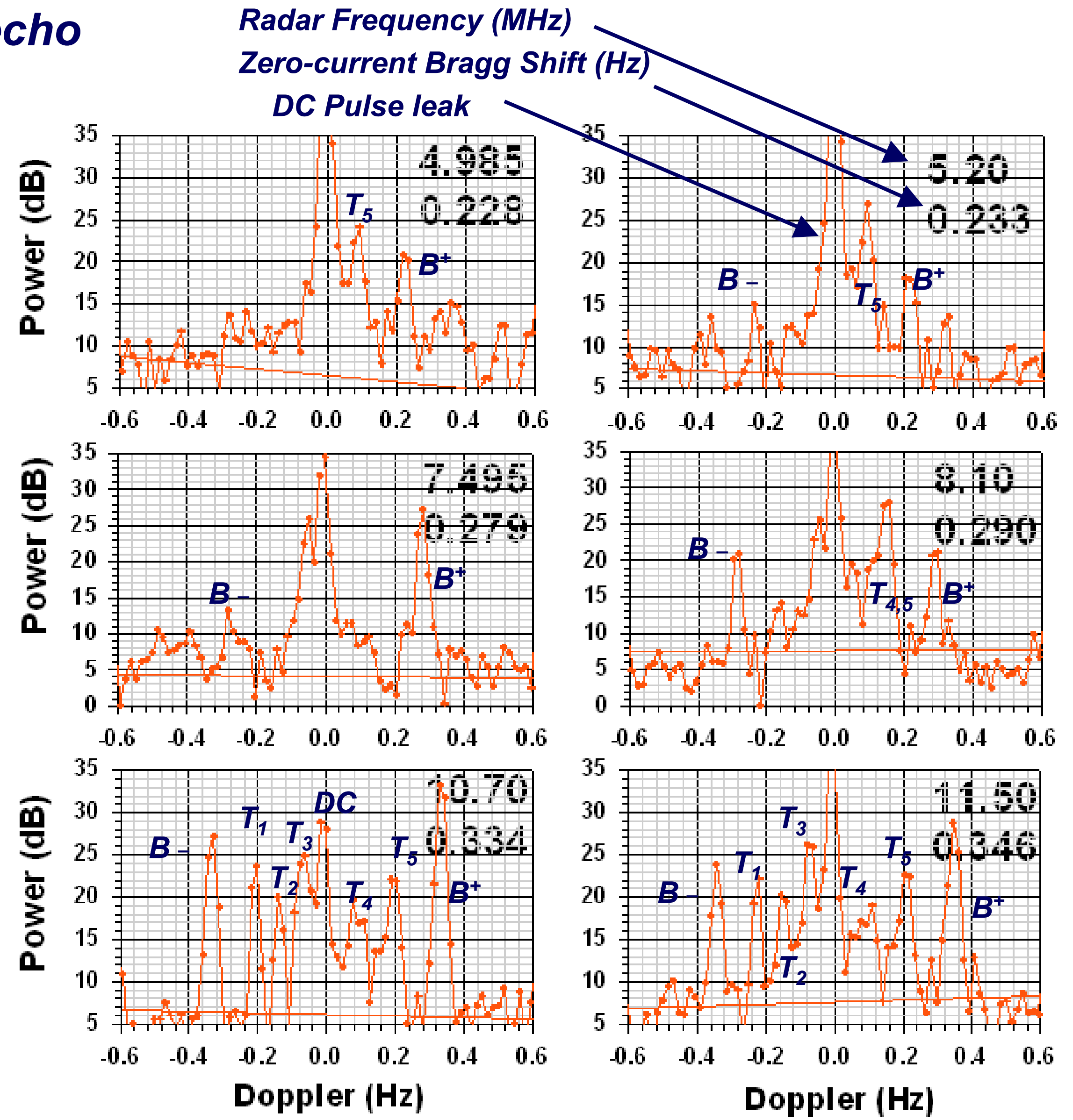
Figure 1. Examples of velocity profiles for simulated u and v and for projected ũ and ṽ. (a) Constant eddy viscosity case. (b) Variable eddy viscosity case. t_k is the dimensionless time scaled by the Coriolis frequency and measured from the beginning of a projection time domain.

Ship Classification (RCS Spectroscopy)

- Bogle, Trizna NRL Memorandum Report 3322, July 1976
- Headrick, Rachuba, NRL Memorandum Report 5309-98-8173

Target Detection: (1)RCS Amplitude, (2)Radial Speed Measure

Doppler spectrum shows sea echo Bragg lines + Target echoes



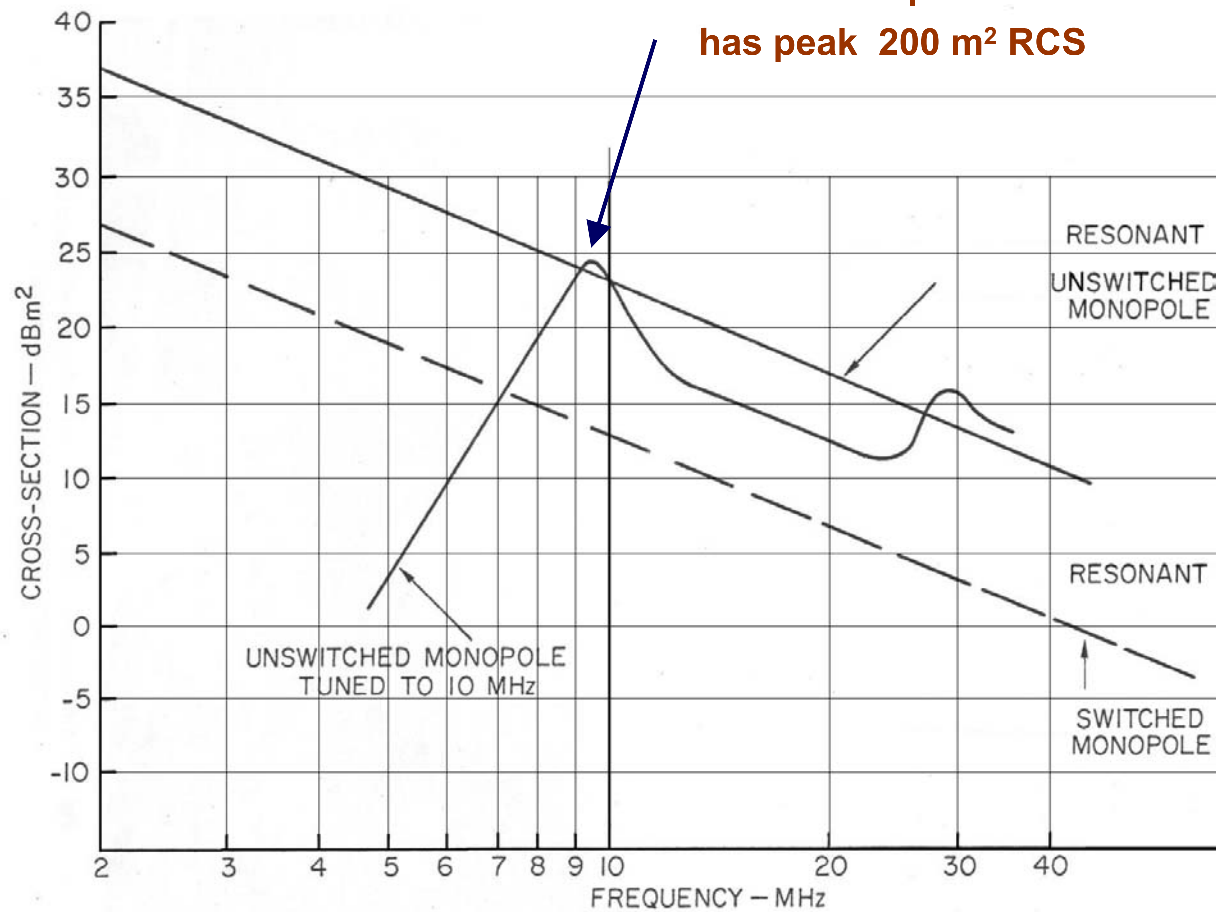
- Radial Speed(kt)=1.94*Doppler/(λ/2)
- 5 targets seen at high frequencies
  - 2 approach (T_4, T_5)
  - 3 Recede (T_1, T_2, T_3)
- RCS~Power, changes with frequency
  - *Use as Target Classifier*
- *Target can overlap Bragg line*
  - *Loss of target track results*
  - Mitigated by multiple Radar frequencies
    - $V_T \sim F$
    - $V_B \sim F^{1/2}$

Model Ship RCS: Bulk Echo + $\lambda/4$ monopoles (vertical structures)

Monopole RCS frequency dependence:

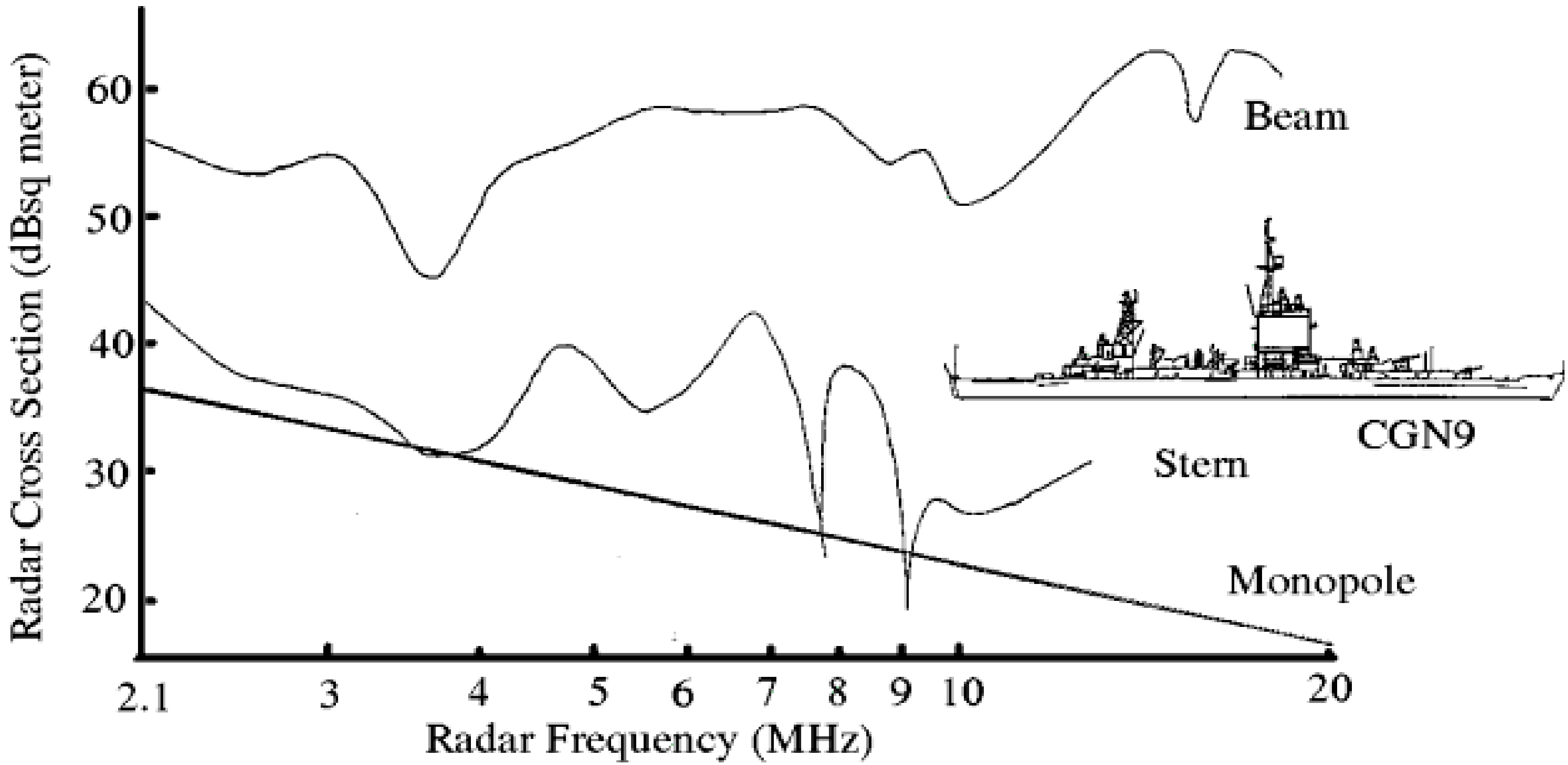
- 10-MHz $\lambda/4$ monopole is 7.5 m high
- Ocean Ground Plane produces image of induced currents, thus a dipole RCS
- 10 Mhz resonant peaks at ~9.4 MHz as shown below
- Odd $\lambda/4$ peaks also appear
- Low Frequency decline as λ^7
- Use as a RCS Calibration tool

- 7.5-m monopole over water has peak 200 m^2 RCS



Large ship RCS is dominated by bulk RCS source beam-on then by monopoles, with interference nulls when observed bow/stern-on

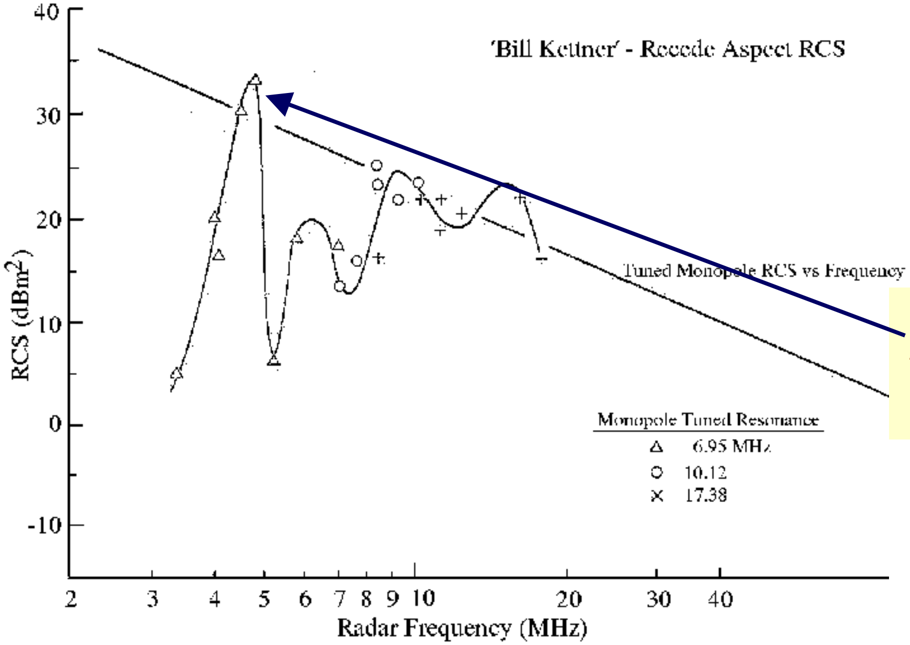
Stern/Bow Vs Beam-aspect RCS ratio is 20 dB or more



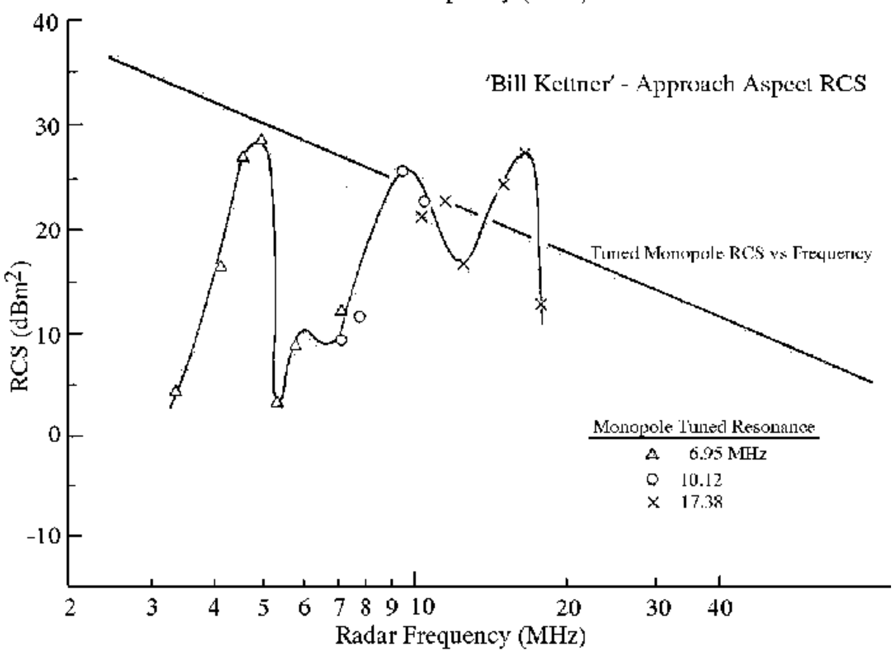
Smoothed curve of beam & stern RCS for CGN9
(Headrick & Rachuba, NRL/MR/5309-98-8173)

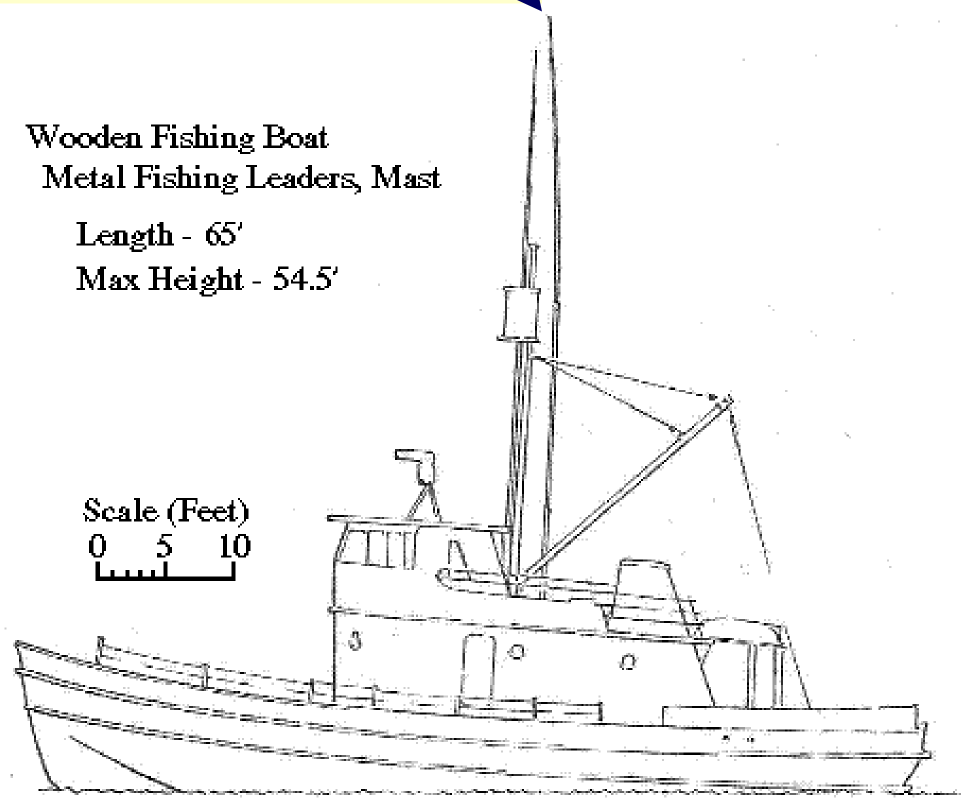
Ship Classification

Small RCS Example - fishing boat (RW Bogle, DB Trizna, NRL Report 3322, July 1976)

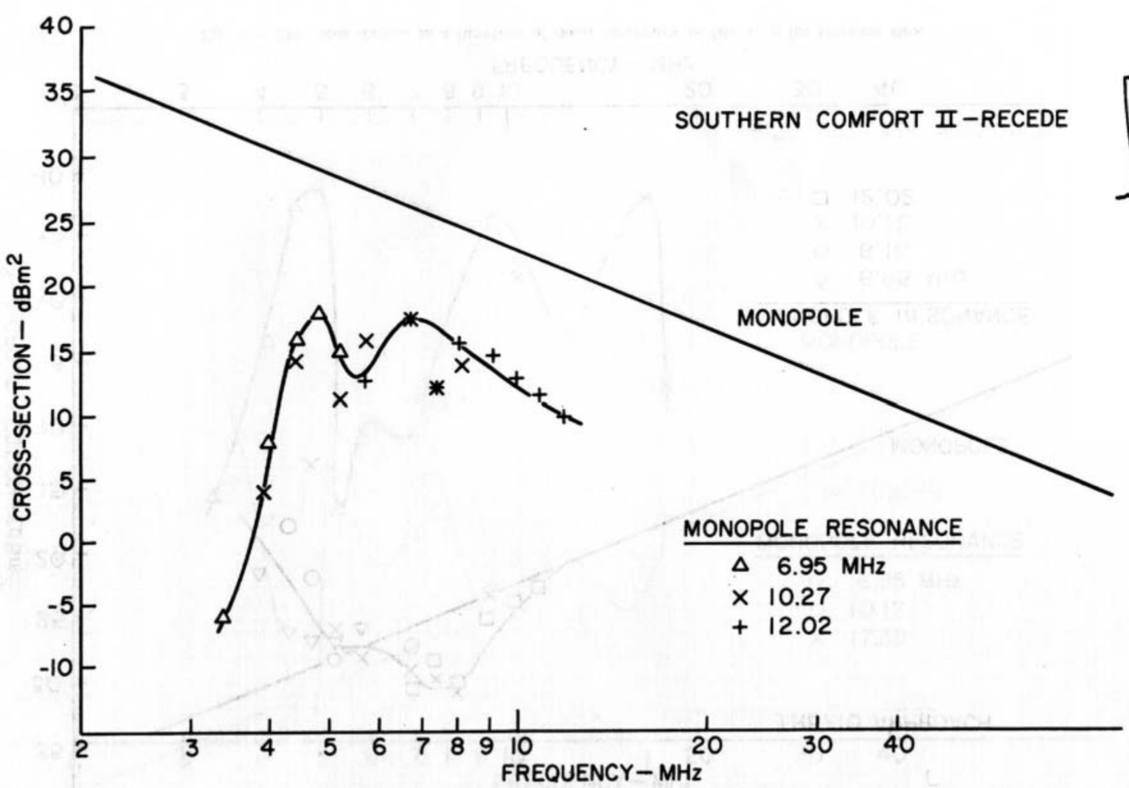


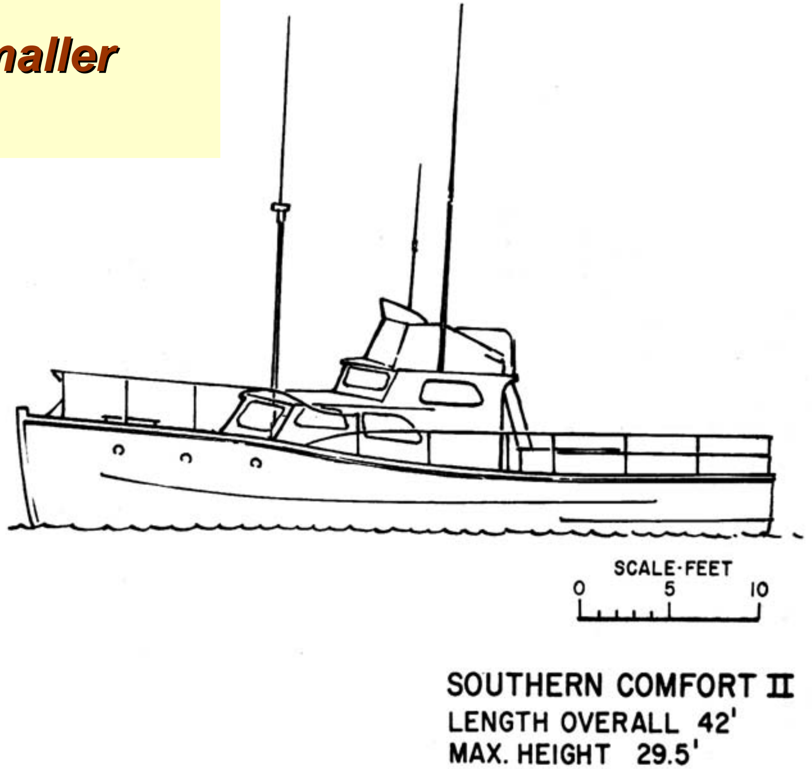
Metal Mast = 54.5 ft = 16.6 m
= λ/4 @ 4.5 MHz





2nd Small RCS Example
Southern Comfort II Pleasure Boat
with possible monopole resonances, but smaller RCS than monopole

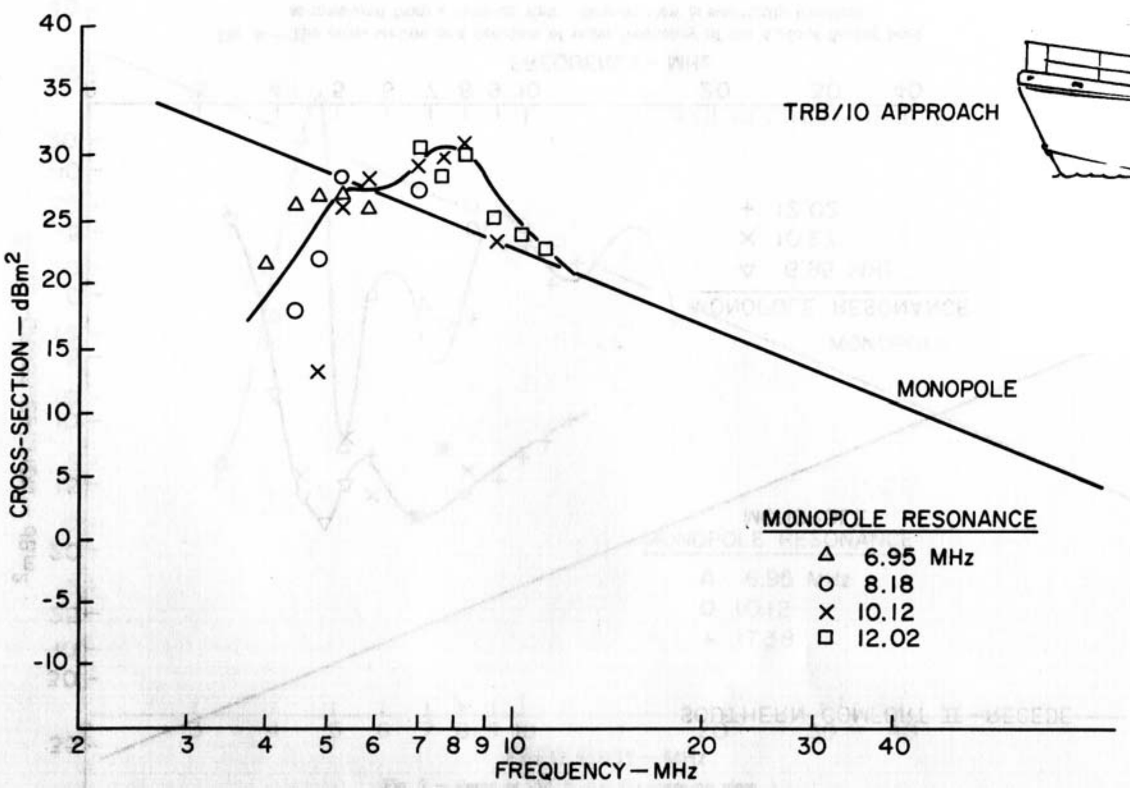


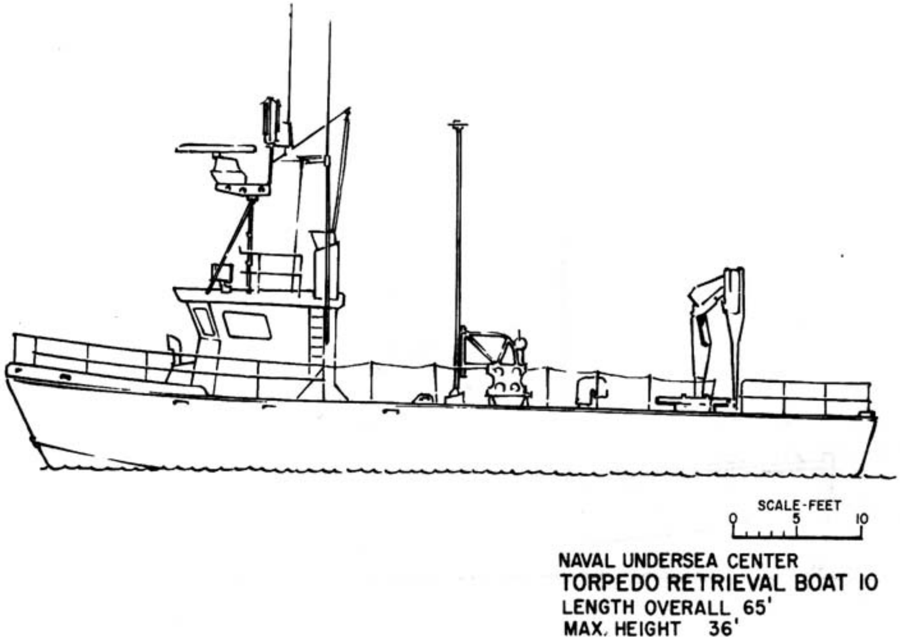


3rd Small RCS Example

Navy Torpedo Retrieval Boat (TRB)

Several monopole resonances





In Summary:

- Boats demonstrate quite different Monostatic RCS Peak and Null characteristics
  - Maximum observed RCS indicative of Ship size
  - Peaks indicative of presence of vertical mast-like structures
  - Deep Nulls indicative of two or more masts, when spacing is $\lambda/4$ x Odd Integer
  - Can be used as ship classification tool
- Added information content is available using Bistatic illumination - 2nd dimension
  - Combined with Monostatic results allows rapid classification
- Multiple Frequencies allow detection and tracking when Target Doppler shift = Bragg shift
  - Target and Bragg lines merge
  - *Can be counter-detection method* against single-frequency radar, if ship is aware of HF illumination and illuminating radar frequency