Coherent Marine Radar Measurements of Ocean Wave Spectra with Vertically Polarized antennas

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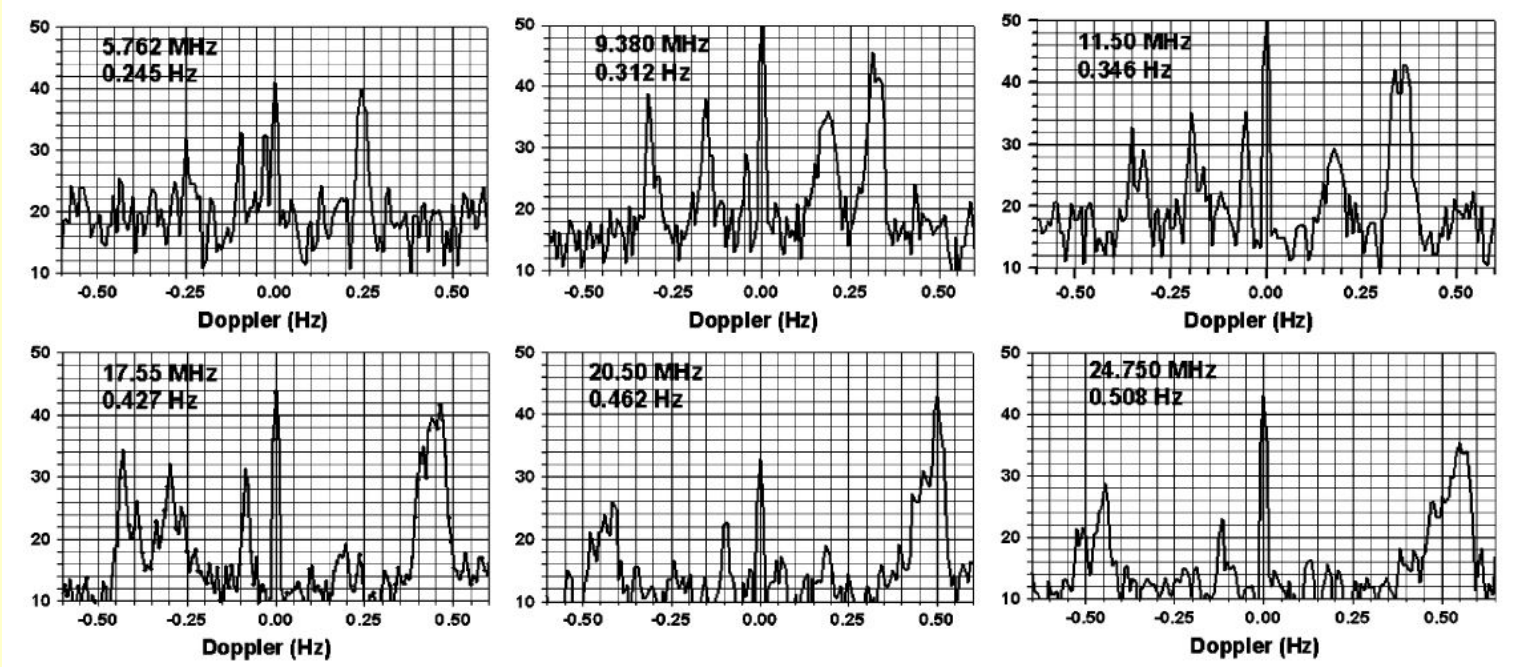
ISR Hardware Development History

- ONR Project 2001-2004 – build a 16-channle Radar Transceiver for HF Radar Use
  - 2001 - Code 31 Surveillance Branch ISR contract
  - 2005 - 32-freq HF radar sold to NSWCCD for ship target RCS characterization
  - 2008 – 2nd unit, GPS-time/Rubidium Clock Bistatic upgrade, sold to NSWCCD
  - 2015 – 2nd pair of bistatic HF radars tp NSWCCD
  - Utilize Quad-Rec card for Standard Marine Radar Applications (WAMOS approach)
- ONR Sponsored Div Research Initiative to Un-Mich, contract to ISR for COHrad
  - 2007 - delivered CORrad (Marine Radar modified – IF interface card)
  - 2008 - built 2 X-band prototype Fully Coherent radars (ISR exp prototype, UMich delivery)
- Developed under IRAD, a single transceiver box for COHrad application
  - 2010 - ISR design, incorporate into single RF box,
- 2013 - develops vertically polarized antenna - eliminates H-pol H_m0 anomalies

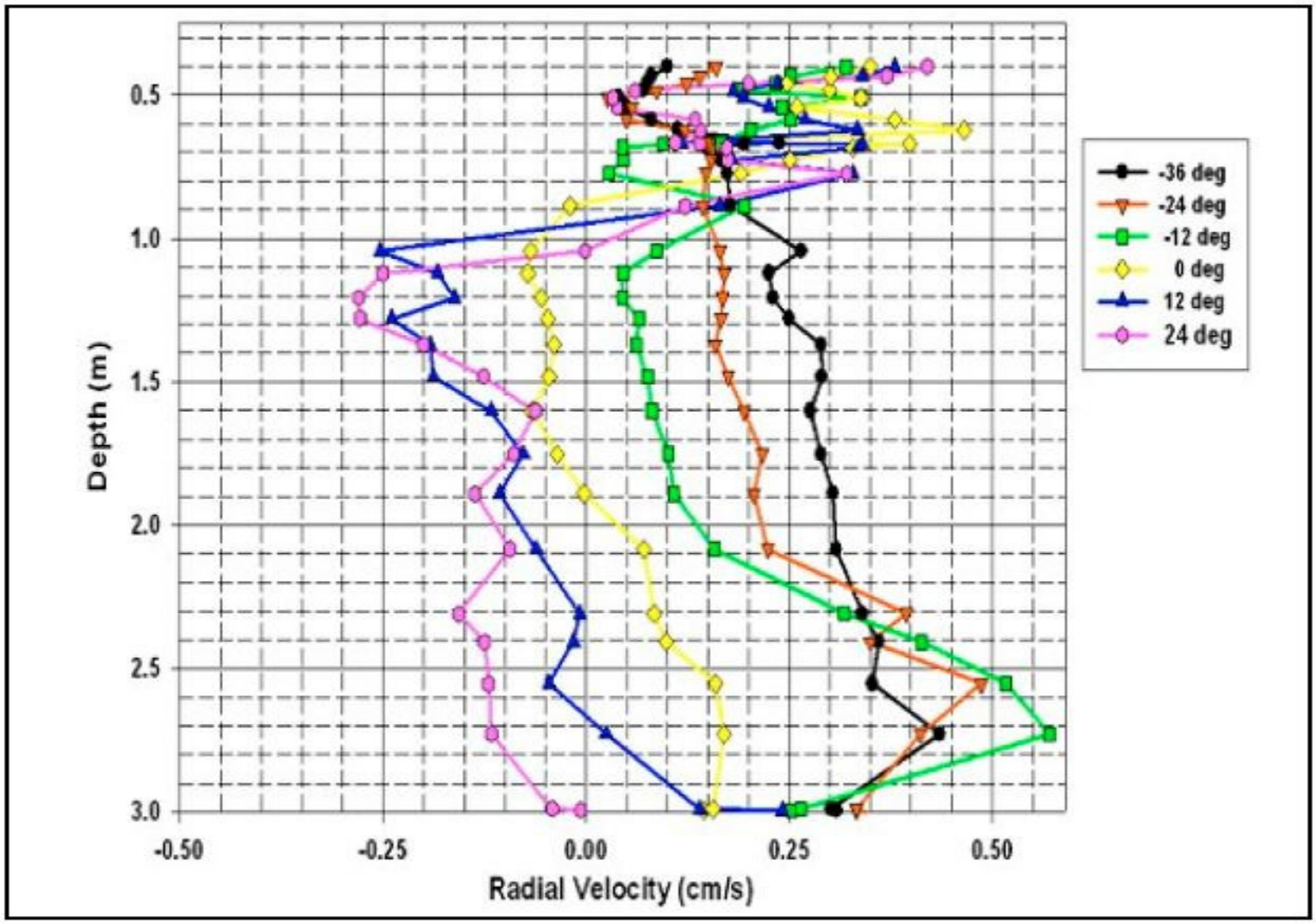
Some HF Radar Results Relative to Current Shear discussions

"Target Classification and Remote Sensing of Ocean Current Shear Using a Multi-Frequency Radar" JOE Vol 31, pp. 904-918, 2005

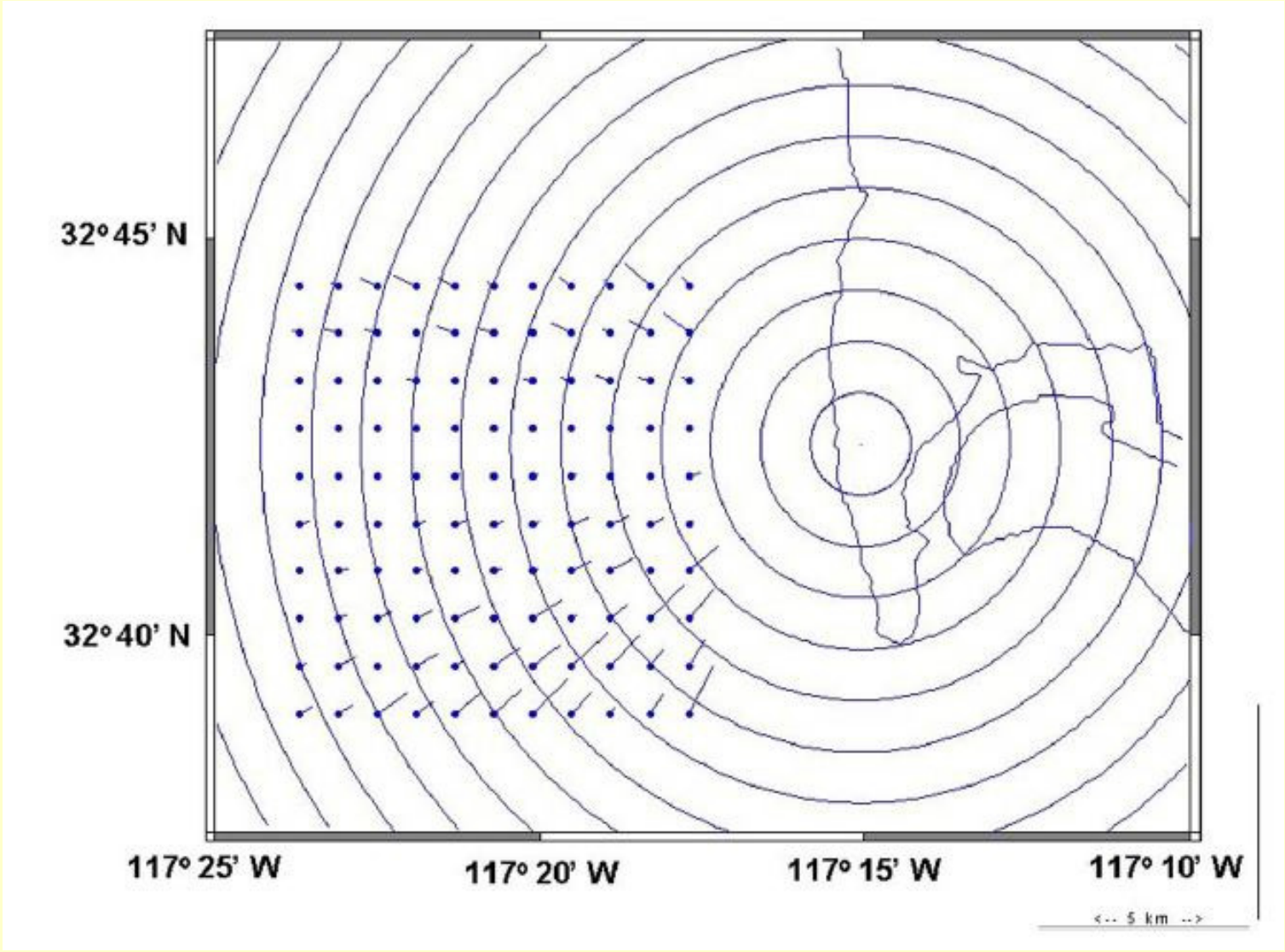
- Used 32 simultaneous frequencies over 2-30 MHz band – ship target RCS measure
- Saw exceptionally broad Bragg lines suggestive of complex current field
- Using 8-element DOA processing, found pattern of eddy structure at depth
- Wind driven log –layer near surface, and random currents between the two



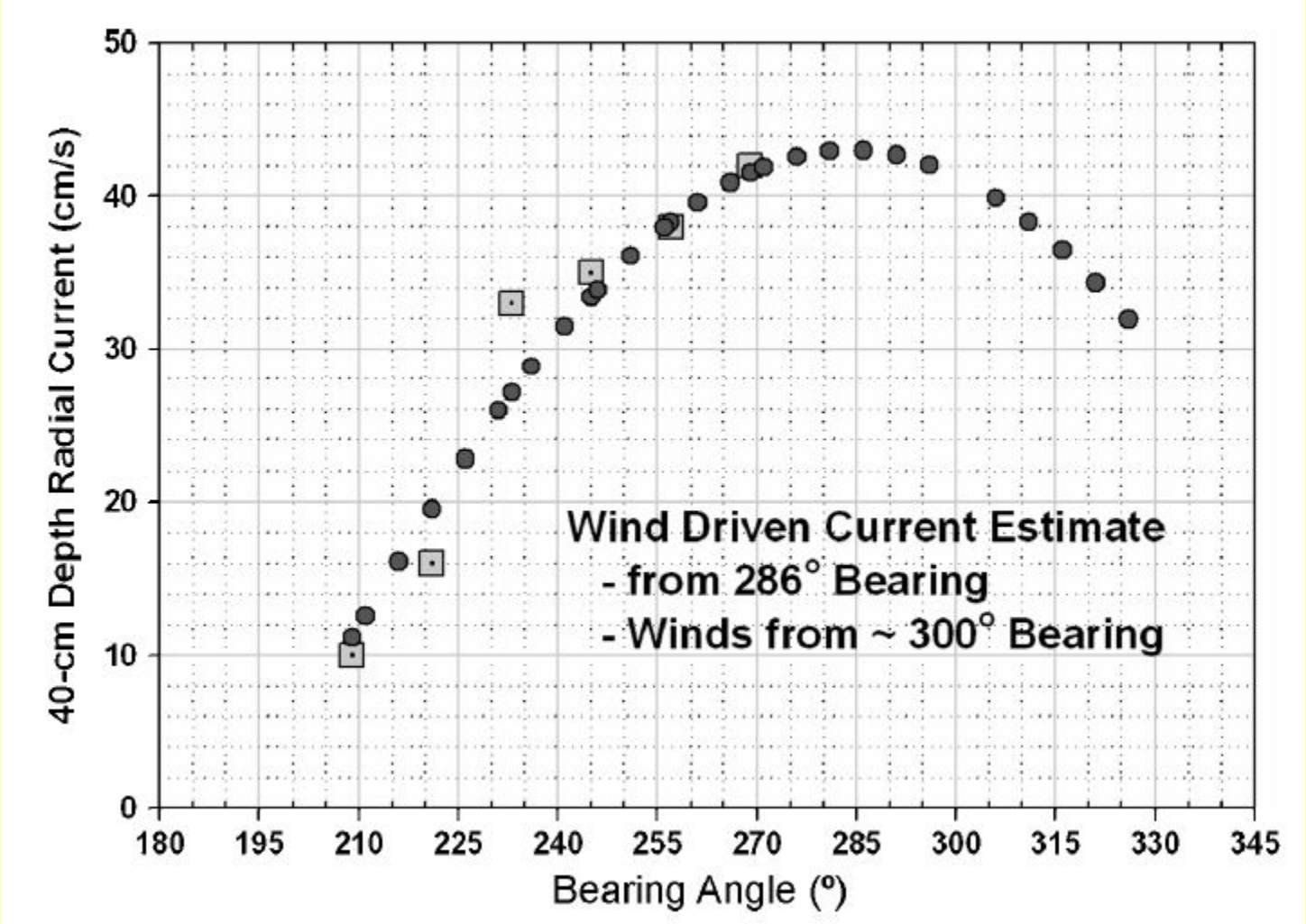
Single Range bin display of Radial currents vs depth



Mid-Frequency set, re-sampled to square grid suggests eddy pattern



Top Layer re-sampled, averaged in range, suggests current along wind

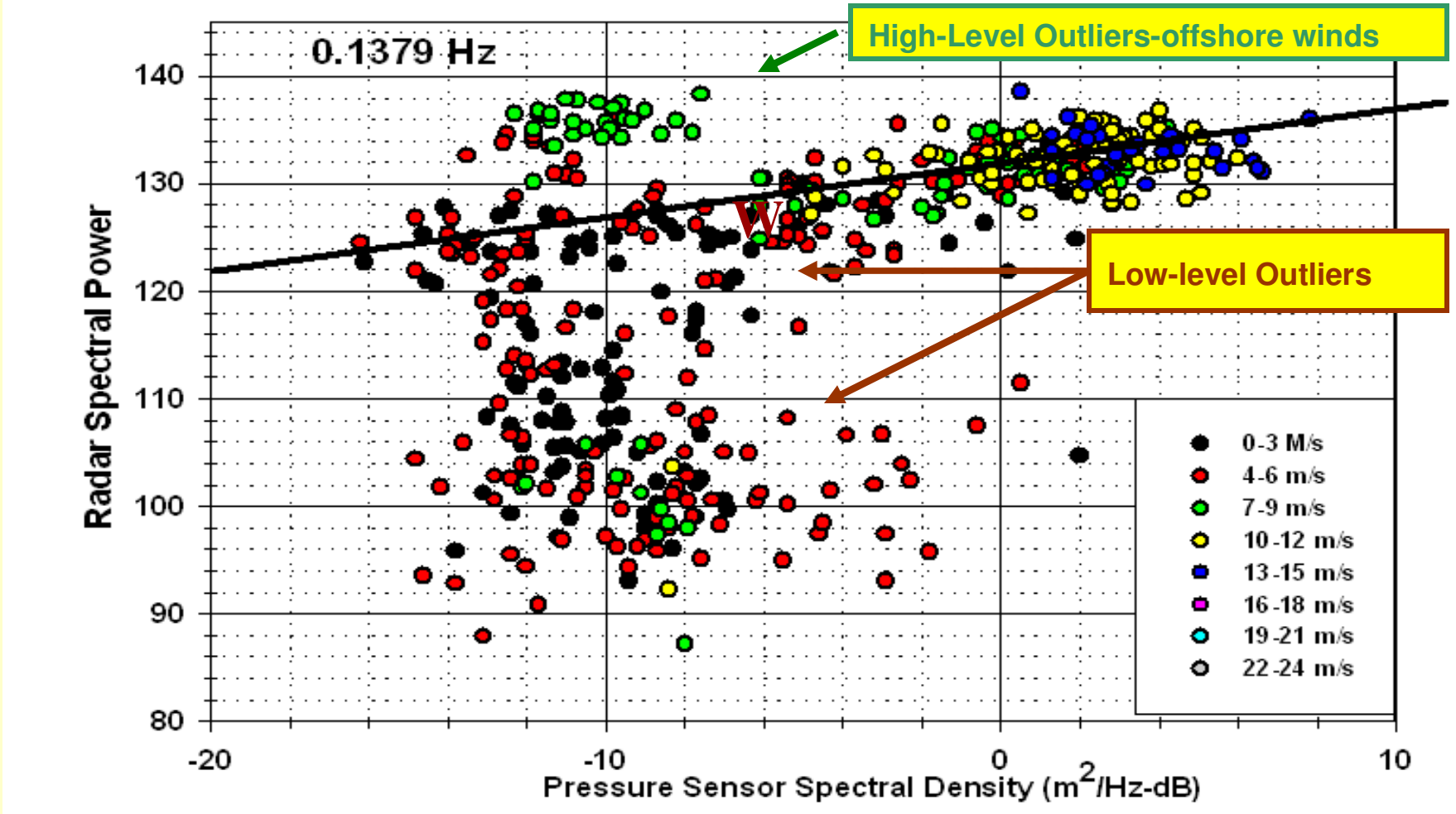


Top 50 cm not presented by ADCP systems can miss this effect

- **Random-like transition mid-depth range suggests eddy feature near surface wiped out**
- **Mel Herron has observed disappearance of eddies at wind onset – mapping VHF currents at river mouths**
- **Surface foam or paper shreds are a better surface truth for mean Doppler current estimated maps**
- **Light to moderate winds, small wave conditions at FRF have provided modest matches between ADCP and mean Doppler currents**

MTF Approach: 1 wave frequency (of 32) plot of K_x,-K_y peaks vs. local buoy surface truth

- **Extract total spectral power from image directional spectra shown earlier**
  - Sum 3x3 pixel area about each of 3 spectral maxima
  - directional aspect of multi-modal data ignored here, peak energies simply summed
- **Plot image peaks vs. Buoy spectrum Spectral Peak Power for 32 frequencies**



Introduction to the Coherent Marine Radar

Standard Marine Radar

- Transmit phase is *random* pulse-to-pulse
- Sum N pulses – SNR Gain ~ N
- Signal is Video ($I^2 + Q^2$) – amplitude only
  - Log-Magnitude Video is recorded
- Radar Wave Images due ~ long-wave slope
- Video to H_m0 is *empirical* - using MTF

Coherent Marine Radar

- Transmit phase is *fixed* pulse-to-pulse
- Sum N pulses, Gain ~N^2, SNR ~N,
- Signal Recorded is I and Q
  - Phase is Φ = ARCTAN(I/Q)
- $\delta\Phi = \Phi_{j+1} - \Phi_j$ ~ Radial Comp. Orb. Vel.
- Orb-Wave Vel to H_m0 is *direct*

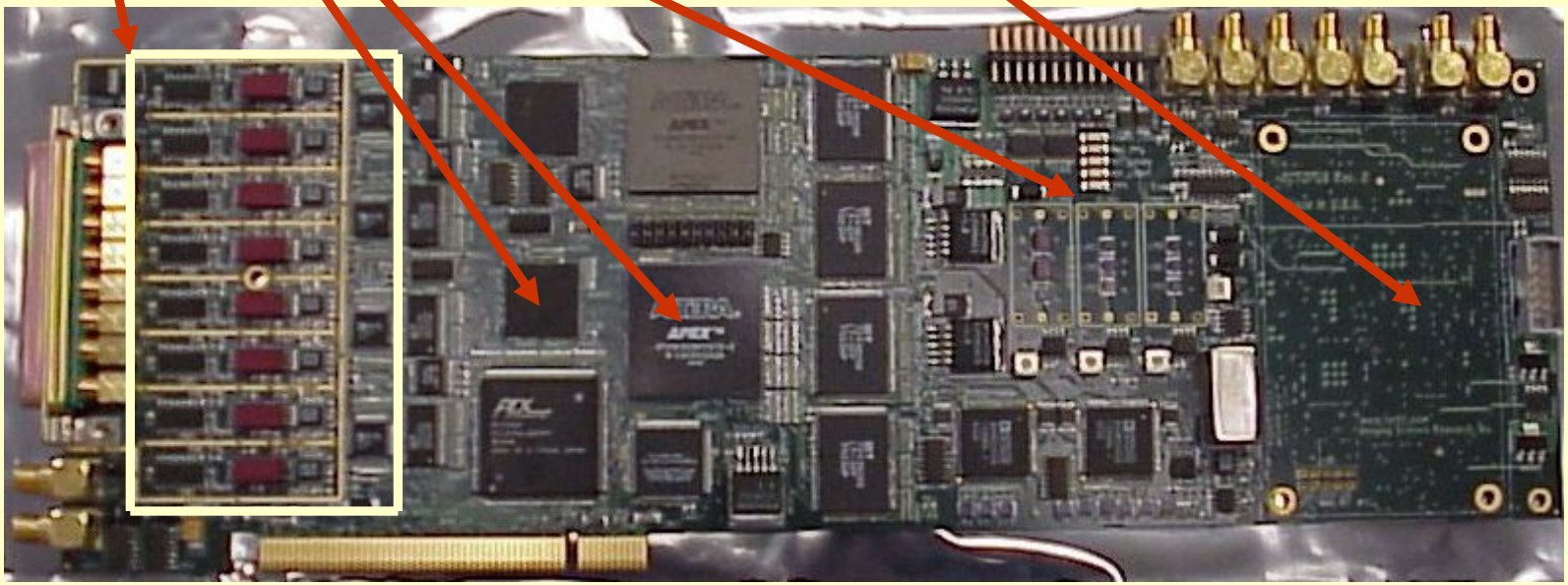
A-Pulse-Generation/Digitization - 4/8 channel Transceiver

Developed under ONR funding for HF radar target applications

50 MHz a/d rate for MRad, 100 MHz for COH/CORrad

Octopus : 8 channel Digital Radar Transceiver – Transmit & Receive

- 8-channel 100 MHz with 1-256 on-board sum =>8 to16 bit + 9-bit digital filter prior to Doppler FFT
  - FPGA's, Digital Down Converters + Cell phone technologies ported to radar world
    - Exciter - transmitter - coherent pulsed waveform digitally generated
      - On-board GPS receiver for bistatic synchronization, location



B-ISR Prototype Coherent Marine Radar Layout:

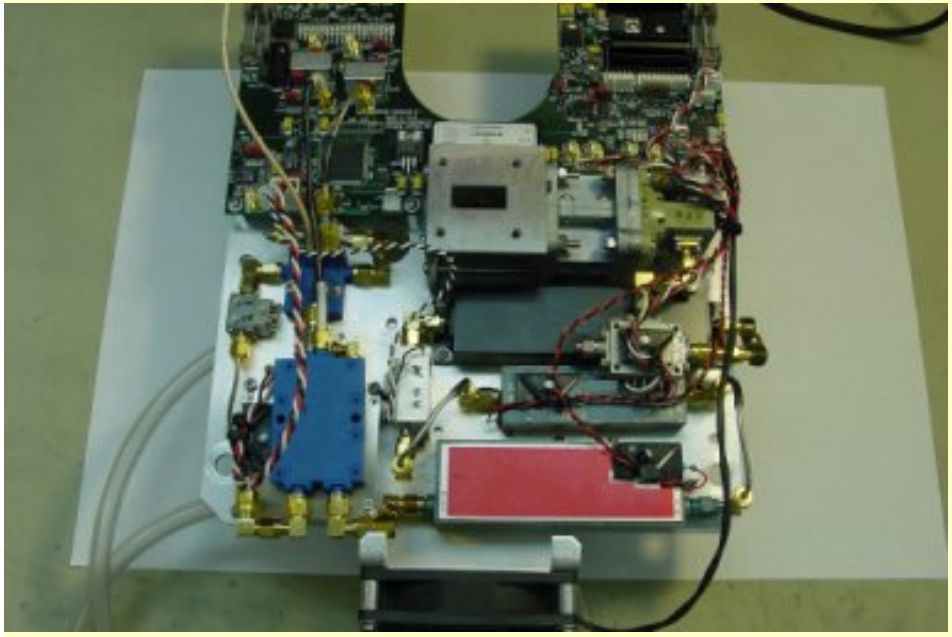
Koden / Si-Tex Radar Pedestal maintained

Above Plane – SMA-Con components

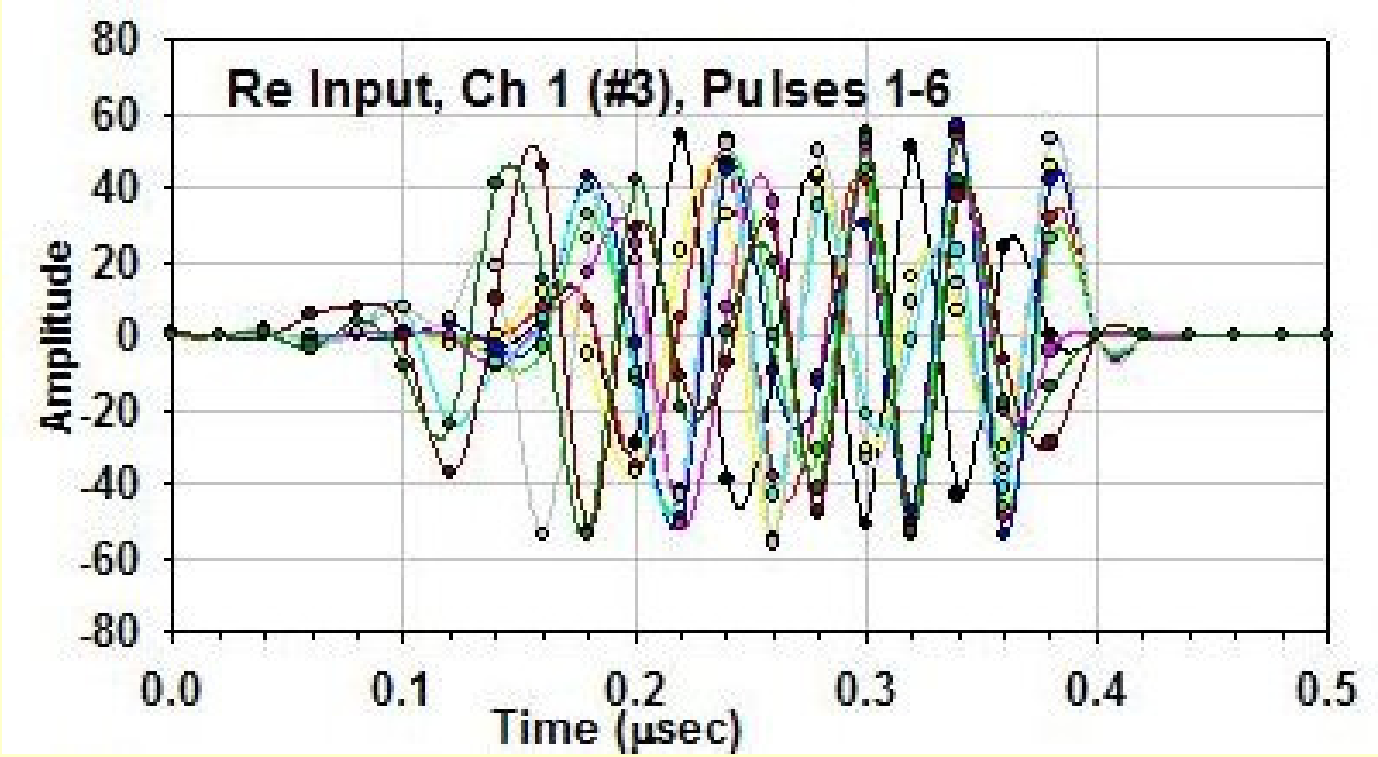
- **Project to combine all elements**
- **Single Package**

Below – Miteq SS Amp, 5 W

- **Cooling system on Prototype**
- **10-min On / 20 Min off ops**



Non-Coherent Marine Radar (MRad)
IF output is a random-phase signal

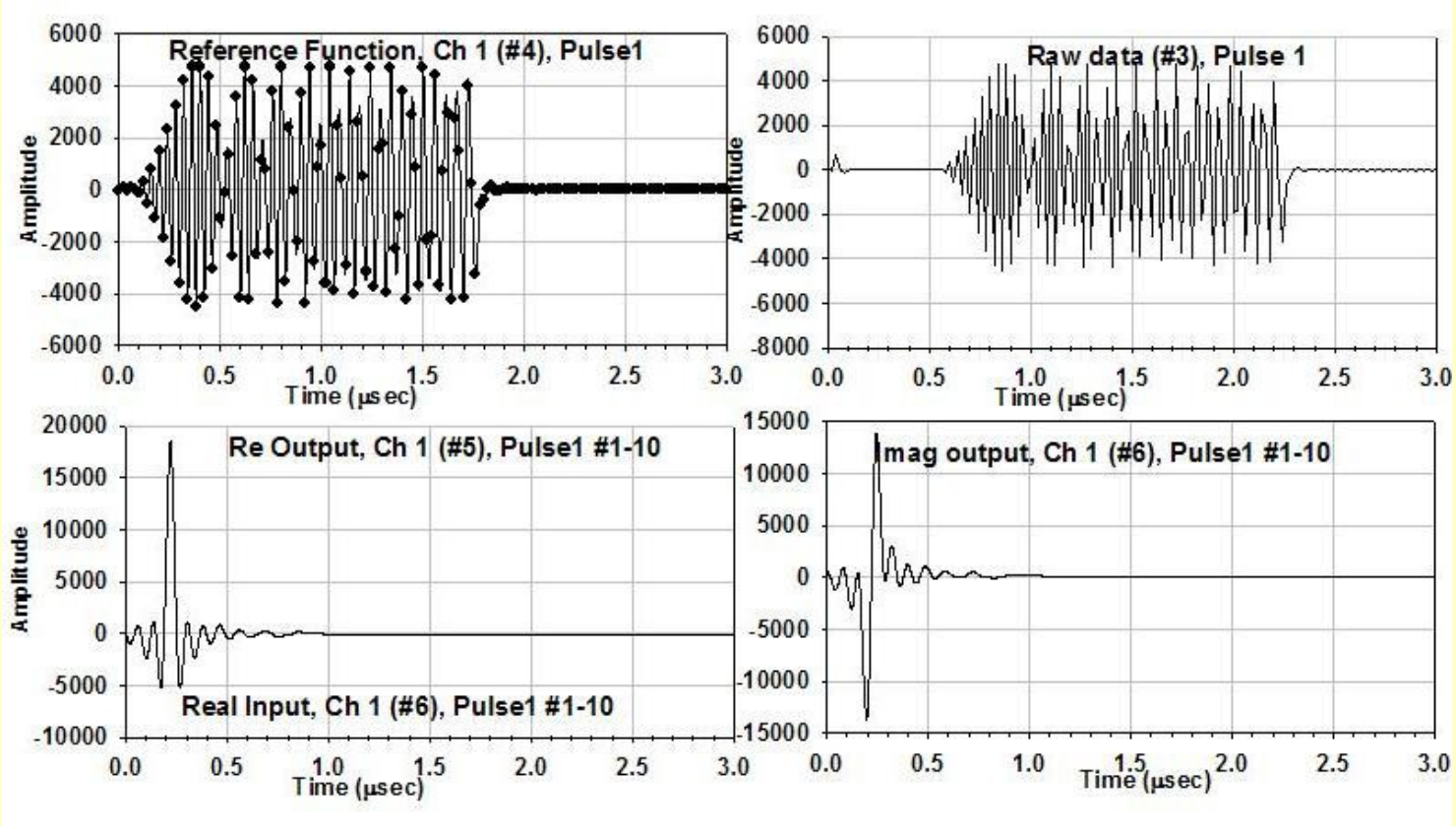


- Magnetron phase is random pulse-to-pulse, as seen above for 6 consecutive pulses
- Local Oscillator frequency can drift during echo time of interest – worse for longer ranges
- Display shows more than transmit pulse, also short range echoes from region adjacent to radar
- Sometime consecutive pulses are nearly the same, then can change phase abruptly
- Cannot be used for Doppler radial velocity measure, as pulse-to-pulse phase difference is used
- Envelope Magnitude is recorded, and echo amplitude creates wave patterns

Coherent Radar - Pulse Compression improves gain:

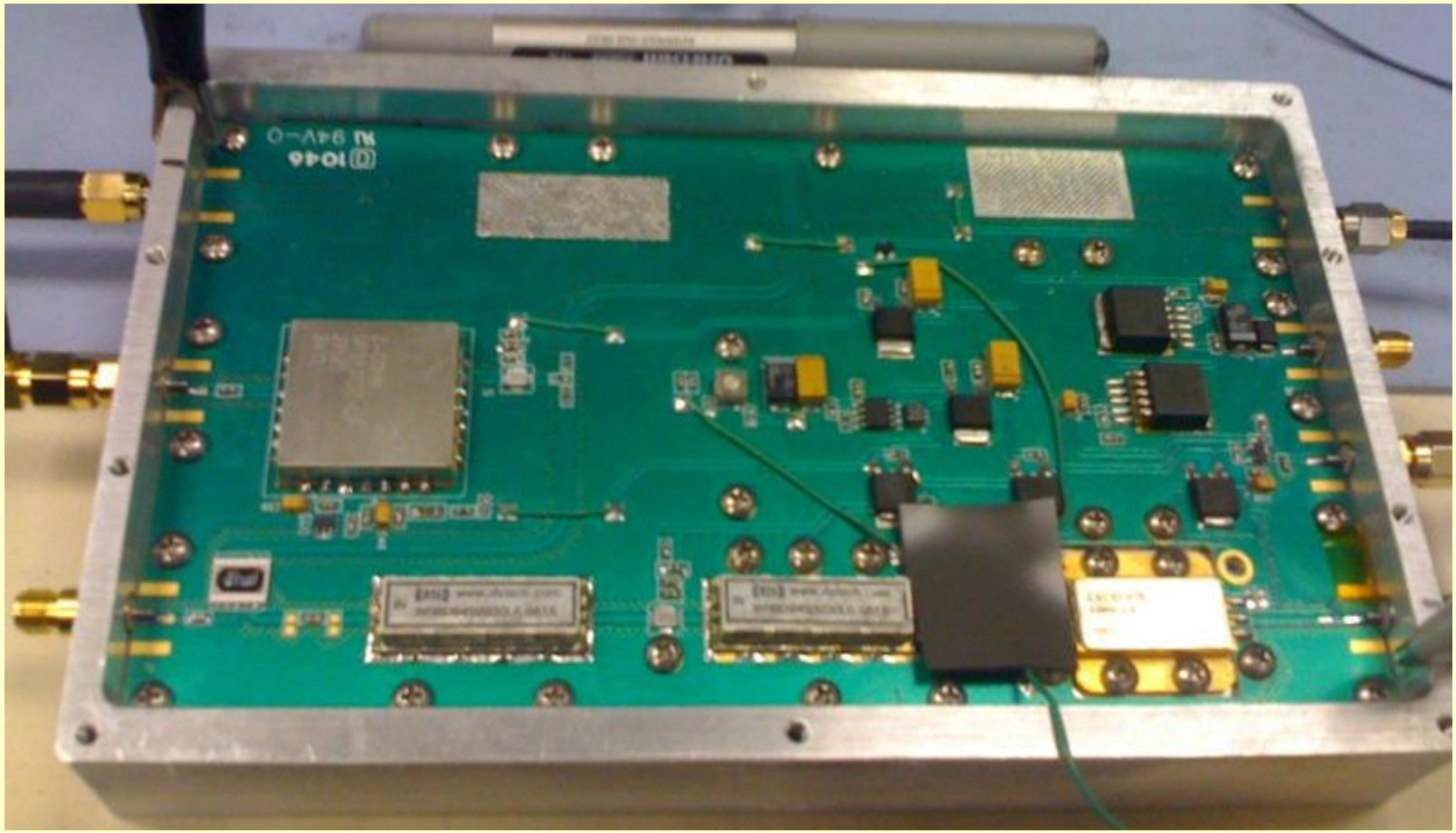
- **In-Phase/Quadrature P-C Output, Sine-Cosine, Point target equivalent**

- **For 30-MHz chirp, get 33-ns pulse echo (vs. ≥80-ns for marine radar)**
- **ATAN(I/Q) gives phase, 2-pulse difference gives radial velocity each cell**
- **$I^2 + Q^2$ gives radar video (magnitude) at each R/Az cell**
  - ***Smaller area/weaker-echo + noise Increase due to wider bandwidth***



C-ISR Solid-state Transceiver Sub-assembly

- Previous components (Top & Bottom Plate)=> on a single board, ~ 4” x 7”
- HPA on bottom now part of Transceiver Sub-assembly – 5 watts output
- Pulse compression (150 m xmit/3 m compressed), plus 25-pulse summing gives equivalent SNR to 12 Kw simple pulse at same 2 KHz PRF recorded



Coherent Radar Processing for Directional Ocean Wave Spectrum Measure

- **ISR Patent 8,305,257: METHOD AND APPARATUS FOR COHERENT MARINE RADAR MEASUREMENTS OF PROPERTIES OF OCEAN SURFACE WAVES AND CURRENTS**

  Additional international filings in Canada, European Union

  Provisional Filing – Sept 2009, Filing - Aug 2010, Granted – October 2012

- **Starting with I,Q pair from COHrad pulse compressed data**
  - **Generate Files for both (1) Magnitude, (2) Radial Velocity**
  - **Associated Text file contains pointing direction of every pulse to .1 deg accuracy, necessary to assure consistent alignment of consecutive rotations**
  - **Cartesian Transform Range-Azim recording for each of Nx64radar rotations**
- **Create Window Clip time stack as with MTF approach, 512 rot = 8 sets of 64**
- **3D-FFT stacks of Radial Velocity Image, take mean spectrum=> Directional Spectrum**
- **Dispersion filter in Kx-Ky space, find peaks => Frequency Spectrum**
- **Sum 32 frequency components => H_m0**

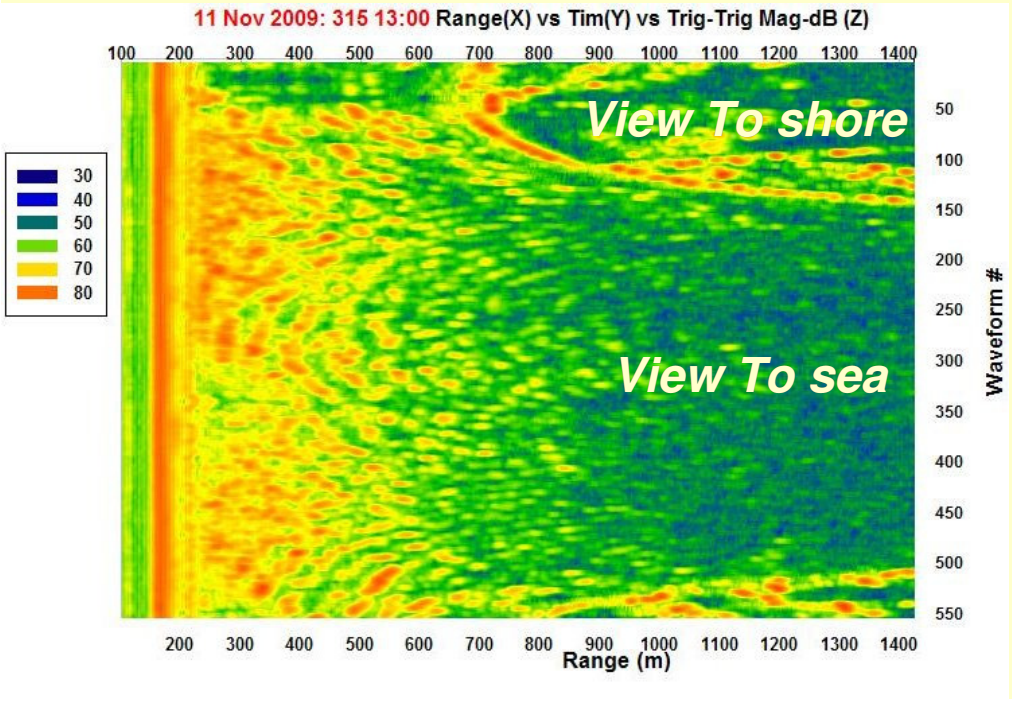
Coherent Radar Magnitude / Radial Velocity – Polar Display

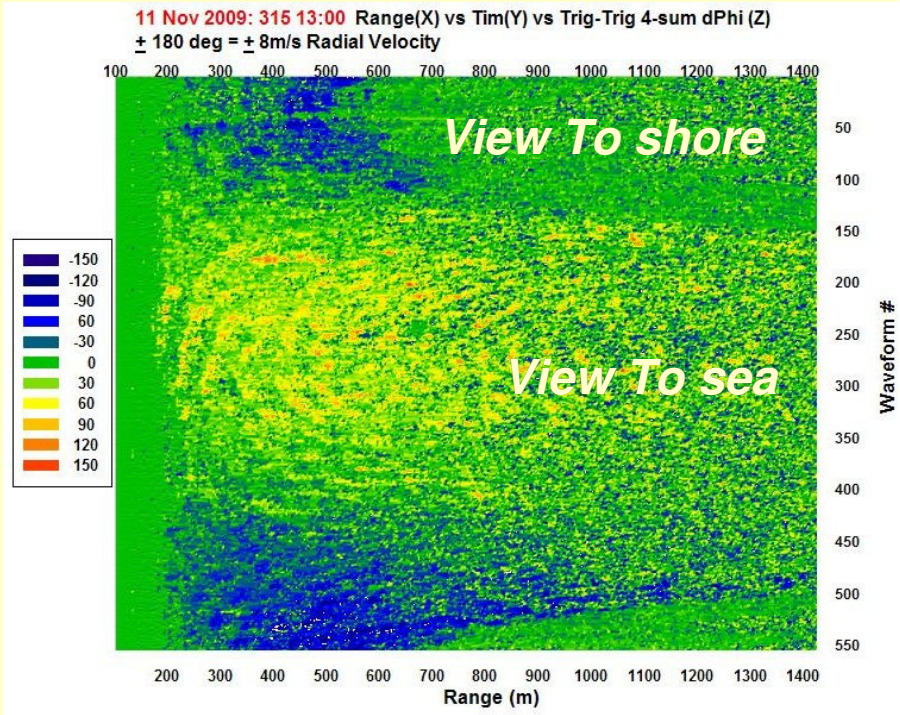
Range-Azimuth Echo Intensity

- Bright is strong echo area
- Wave crests give strongest echo
- Shallow Wave Breaking strongest
- Deep waves breaking less active

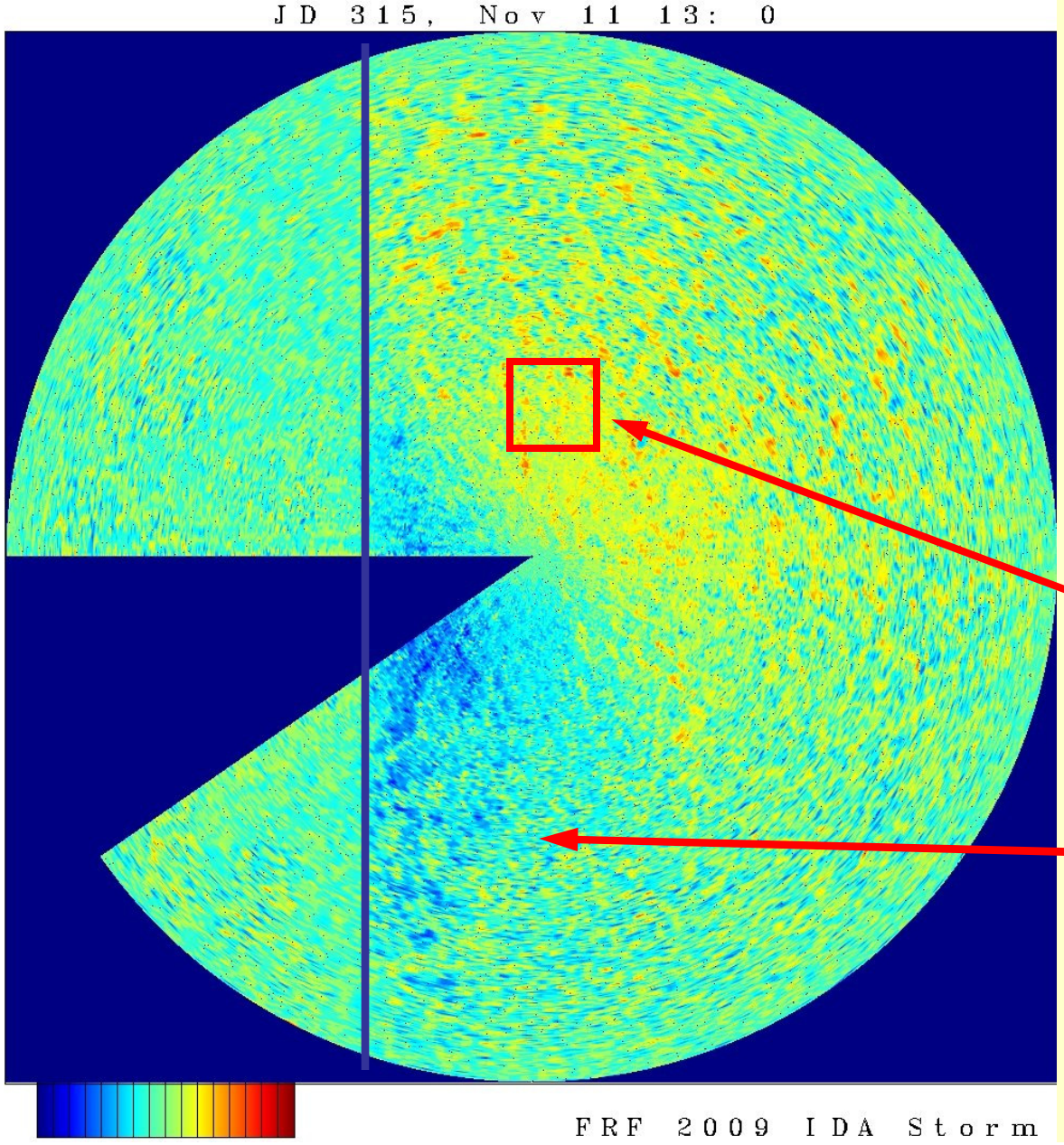
Range-Azimuth Radial Velocity

- Wave-Ht ~ Orb-Wave-Velocity
- Dark = receding, Trough OWV
- Bright = Approach Crest OWV
- Shallow crests faster
- -8 to +8 m/s for 2 KHz PRF





Cartesian Transformed Radial Velocity Maps



11 Nov 11 - Cartesian Transformation of Radial Velocity Image

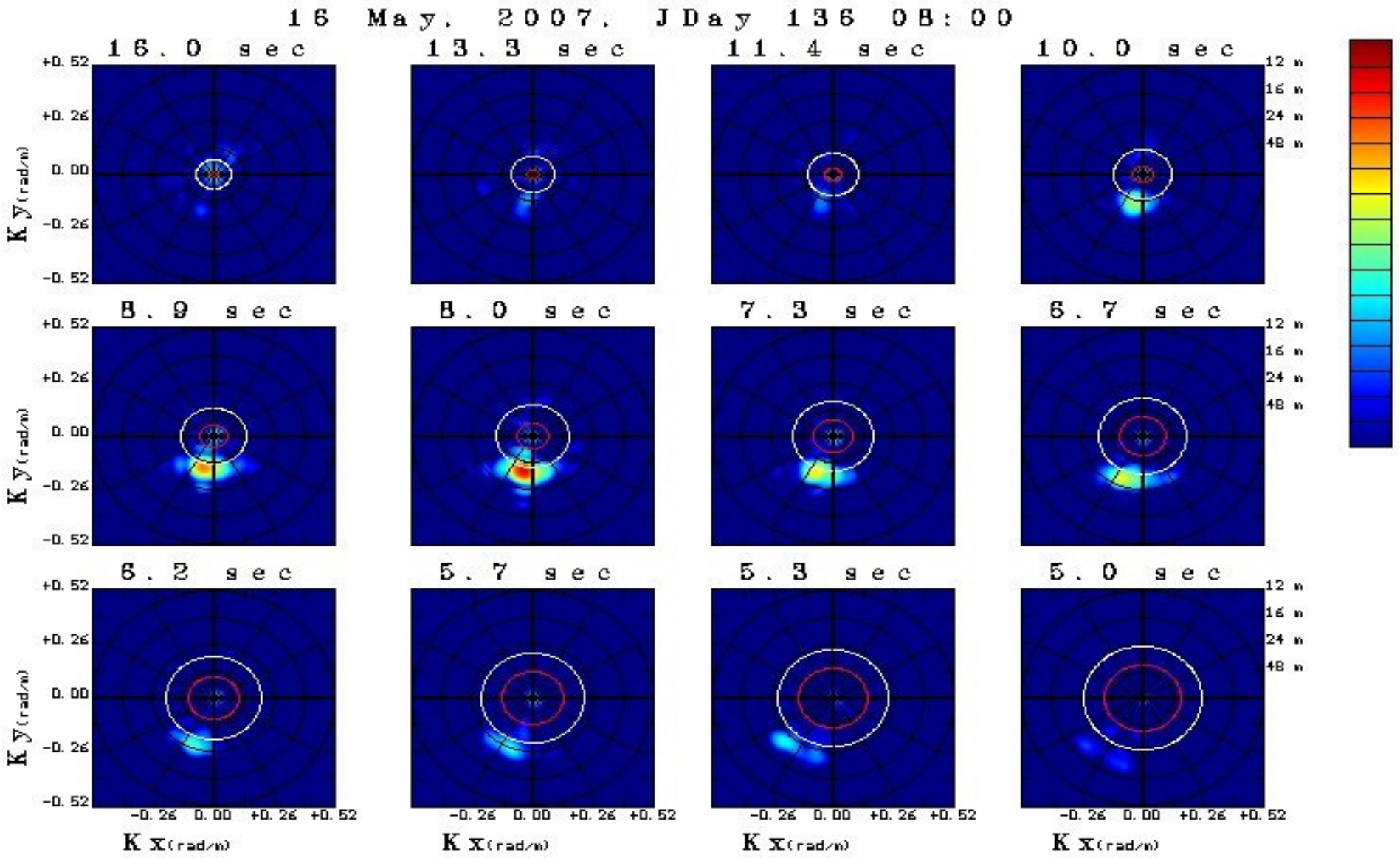
- Shoreline lies vertically
- Recede Doppler is darkest
- Approach Doppler is whitest
- Shoaling waves show higher Doppler shift than deep water
- Set 64x64 window for 3D-FFTs for directional wave spectra
- Use data directly for wave height maps in real-time forecasting apps

Doppler sense lines up with wave direction - dominated by orbital wave motions

Wavenumber Spectra

3-D FFT Output: Again Ω-K Directional Image Spectra, No MTF used!!

Note that now spectral peaks fall off in amplitude relative to lowest frequency peak – Phillips Asymptote



COH Marine Radar results

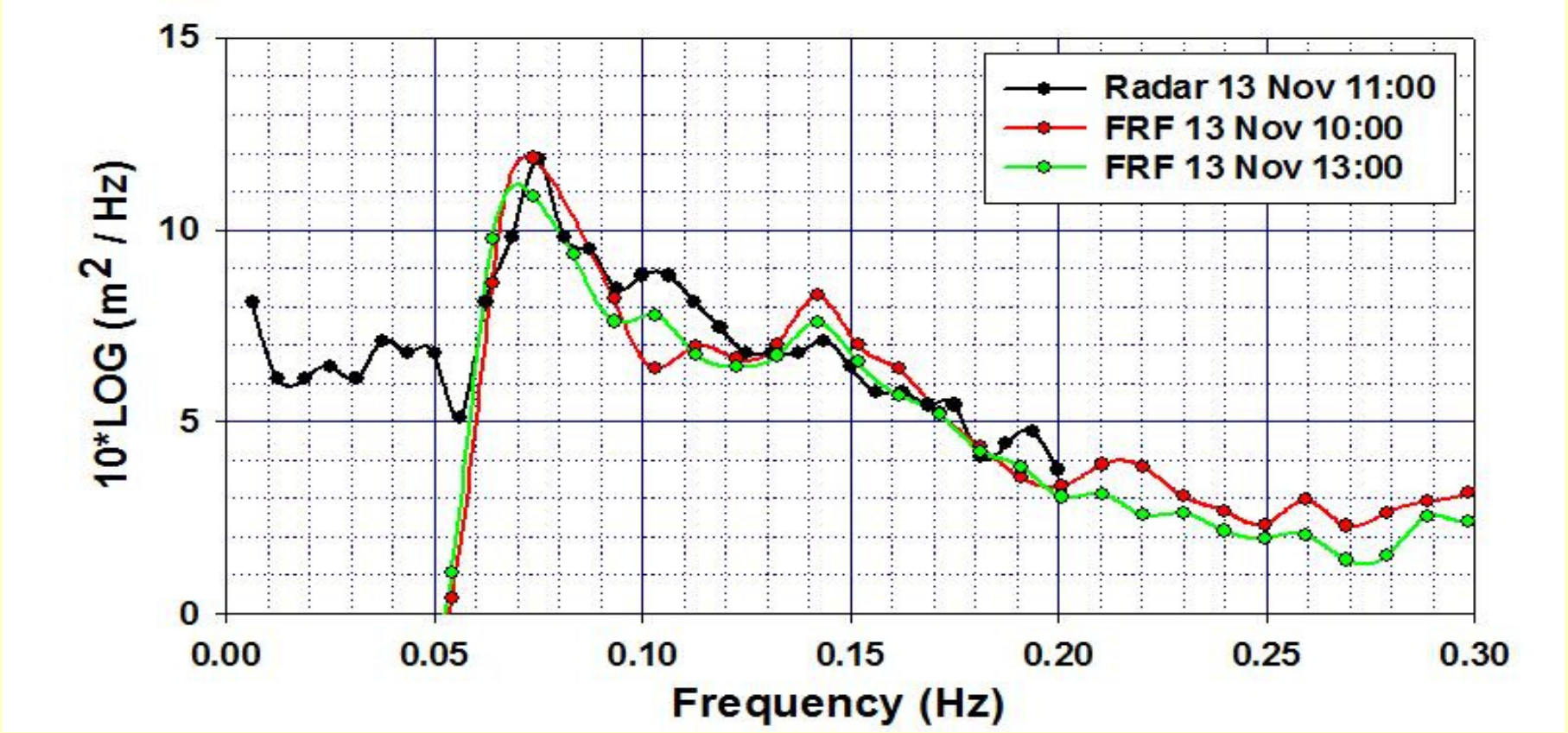
11-13 Nov 2009 Storm, Duck NC test site

Frequency Spectrum derived from Previous Figure

Doppler 3D-FFT Spectral Peaks-512 rotations, 11.6-min

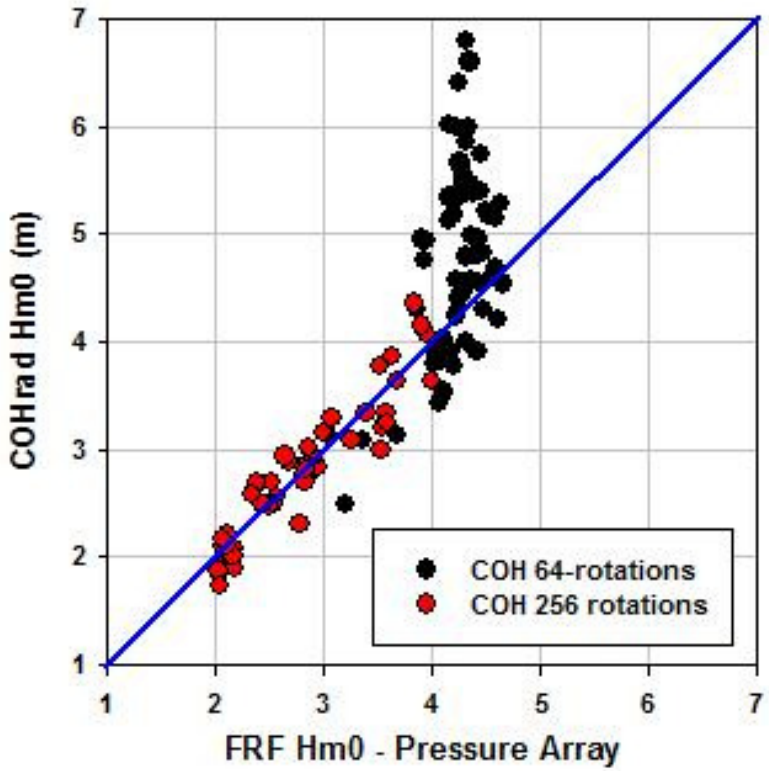
***** No MTF Scaling Required – Direct Measure *****

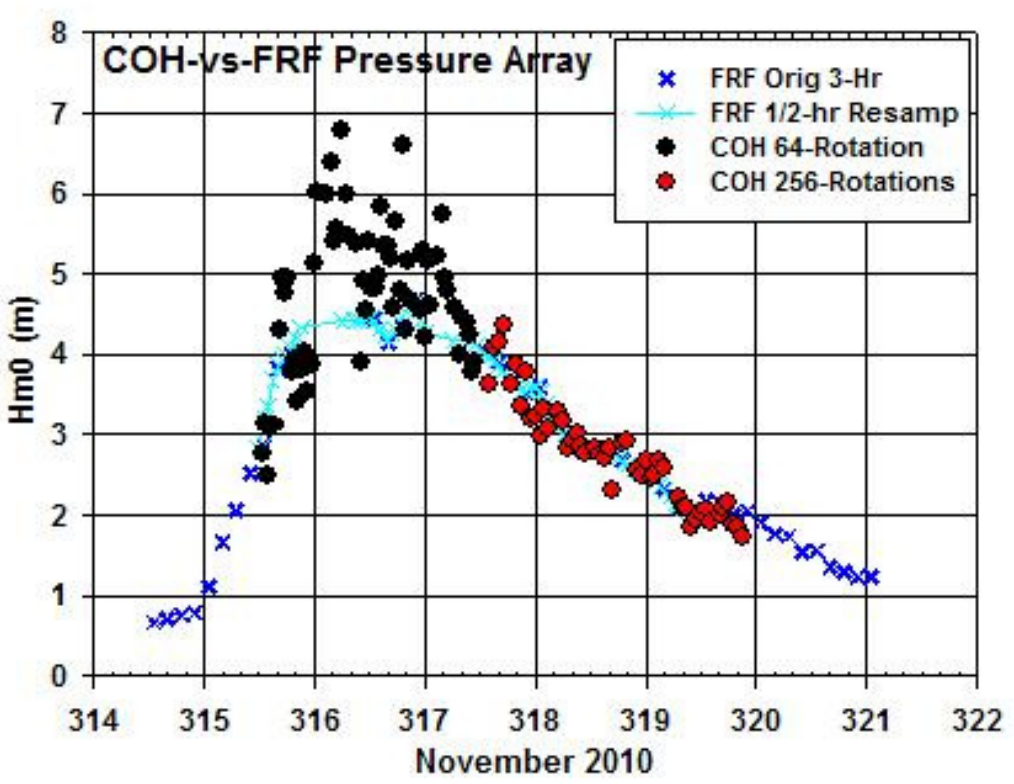
Sum over all frequencies to get H_m0



Veteran's Day 2009 storm - COHrad vs. FRF Array H_m0 Comparisons

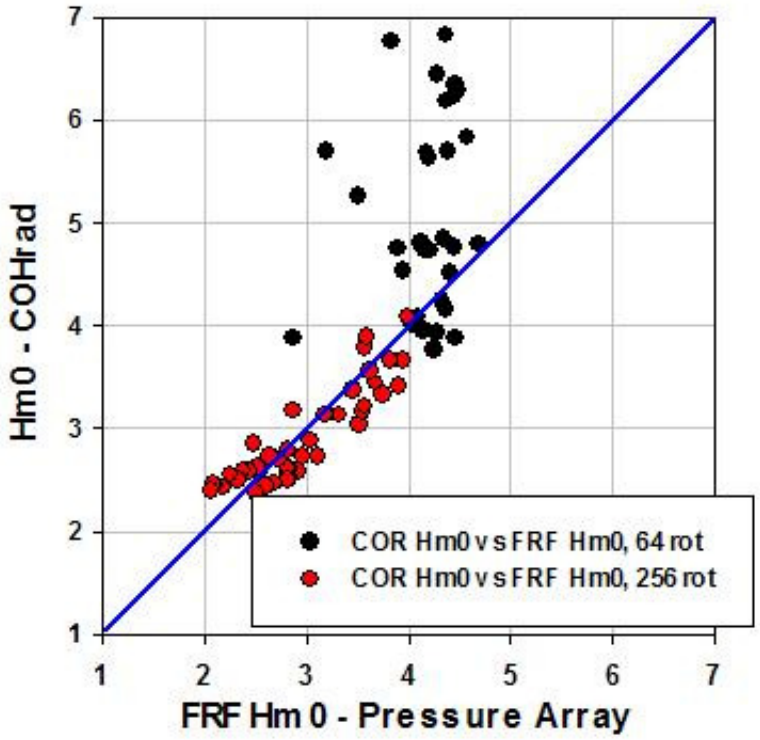
- Good Agreement for 2– 4 m H_m0, poor at higher Values
- Outliers due to wave breaking effects on standard H-pol antenna
- Effect less pronounced at azimuths off perpendicular to incoming breakers
  - Suggests scattering mechanisms effect – crest feature appears as a resonant dipole scatterer

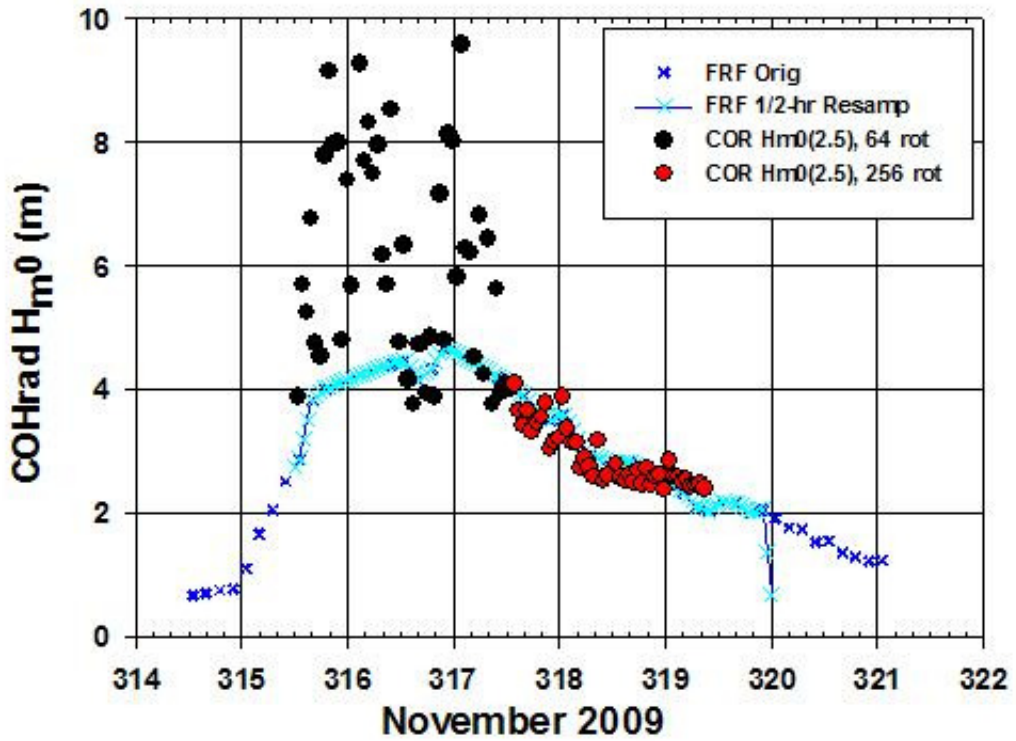




Veteran's Day 2009 storm - CORrad vs. FRF Array H_m0 Comparisons

- Results similar to that for COHrad data – over estimating above 4-m
- Samples were at ~ 250 m past pier of 600 m length – long waves shoaling here



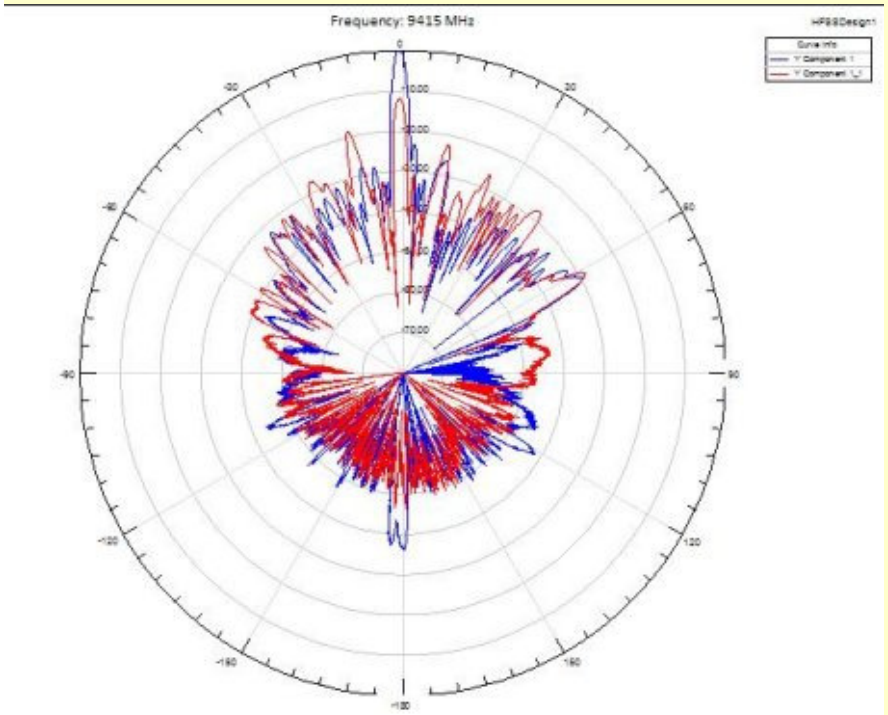


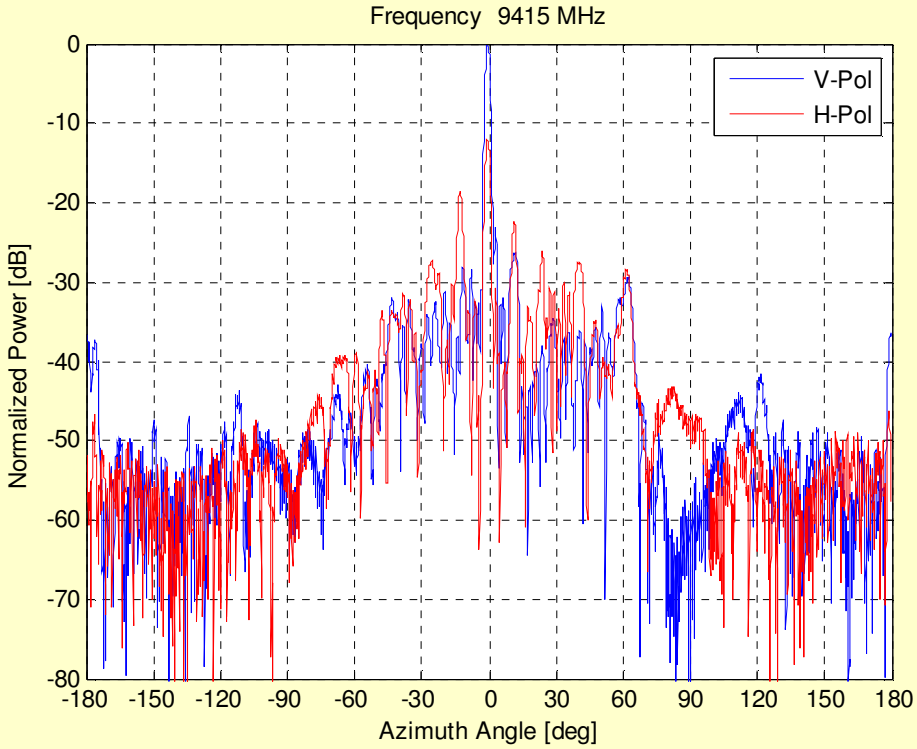
New ISR Vertically Polarized Antenna

- Breaking crest known to produce strongest HH echo
  - Trizna, Carlson - IEEE Trans. Geosciences and Remote Sensing, 34, pp. 747-757, 1996.
- V-Pol antenna minimizes large echo from breaking wave features, better H_m0 results
  - Now building in-house, as original source closed business
  - End-fed slotted array, 4' and 8' units available
  - Installed on approach of Hurricane Irene, 4.2-m wave maxima

New ISR Vertically Polarized Antenna

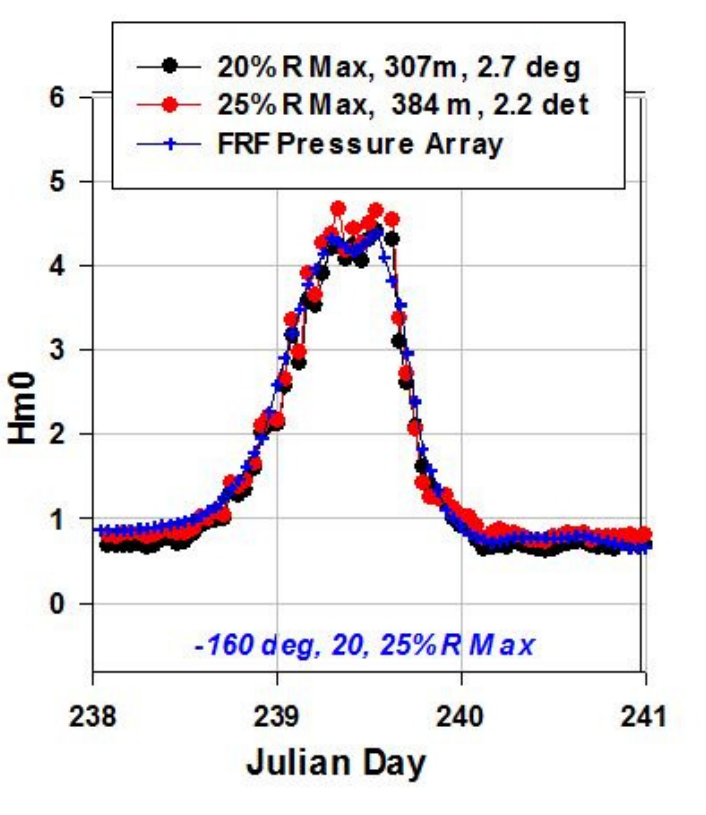
- Antenna patterns measured at Ohio State University antenna test range
- First/primary side-lobes down 30 dB
- Two sold to Michigan State Un, one on hold for Ohio State Un

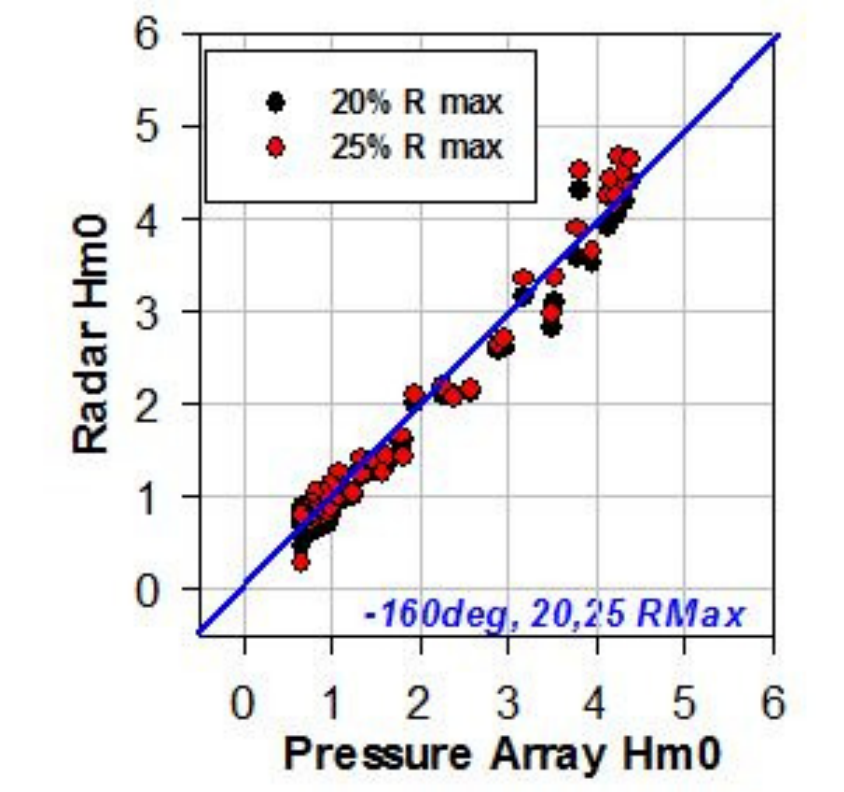




Hurricane Irene – 1st opportunity to test Vertically Polarized Antenna

- Breaking crest known to produce strongest HH echo
- V-Pol antenna minimizes echo from large breakers - no longer sees horizontal dipole
  - Antenna built in-house, 4' and 7' array apertures
  - Installed on approach of Hurricane Irene, 4.2-m wave maxima
- Results are encouraging – confirm hypothesis of wave breaking effects on H_m0





COH -256 Summed Images - Video Intensity (l), Radial Velocity (r)

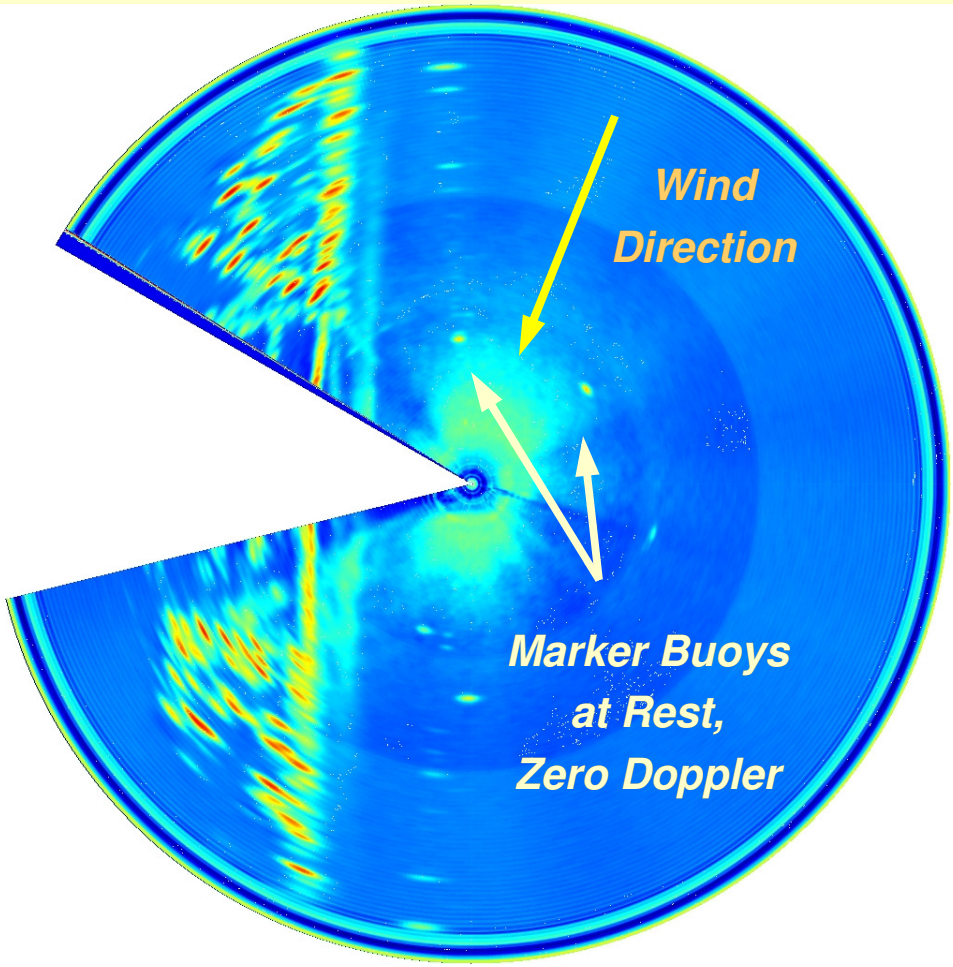
Surface current is dominated by wind drift for high winds

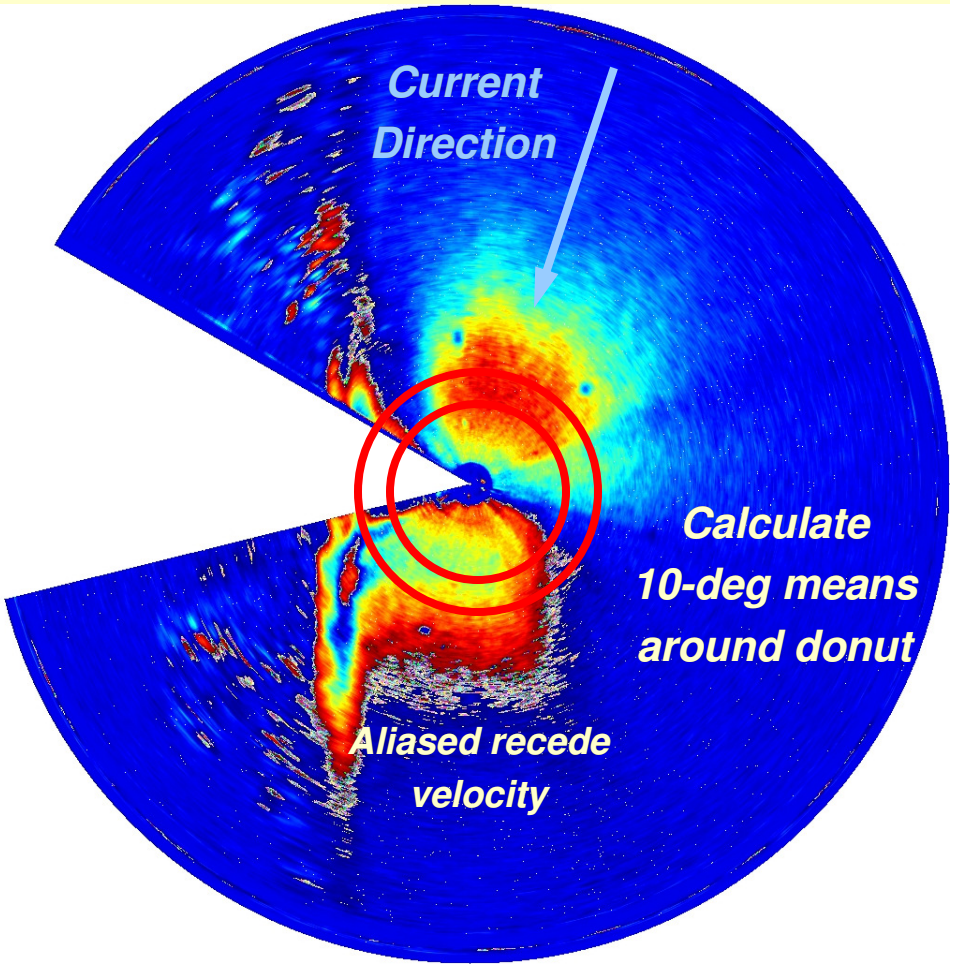
Bragg waves ~ omni-directional, contribute little Doppler shift ? (mean is 0)

Wave Height is determined by modulation about the mean

Surface current is the local mean

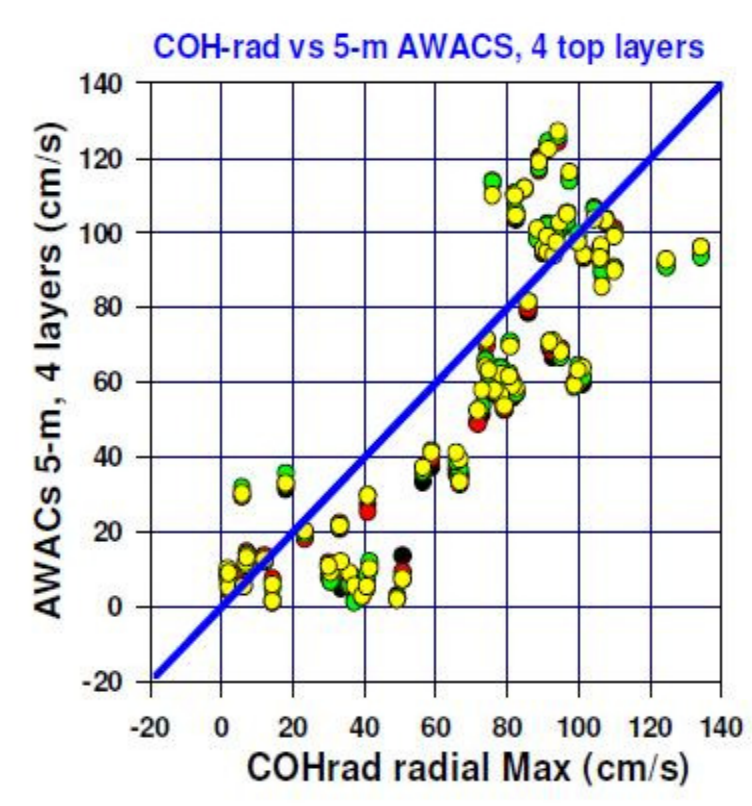
***** Blue dots on right are stationary buoy echoes - Mean Doppler is 0***

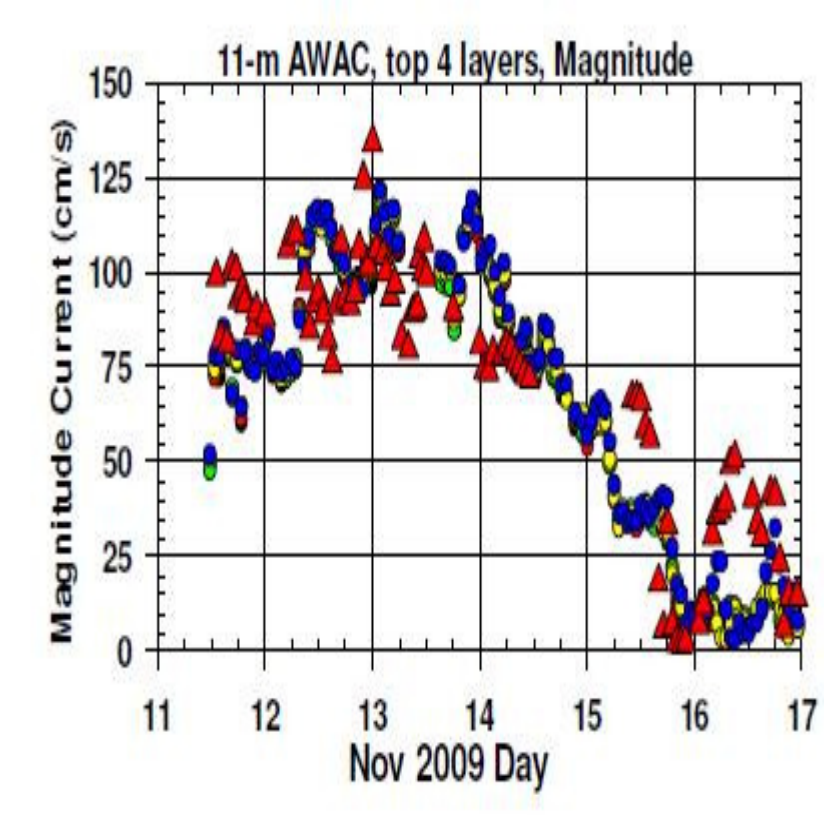




Mean Surface Current Comparisons at FRF

- 10-deg Means of Radial current calculated over azimuthal coverage
- Maximum mean value used as current magnitude
- Comparison with magnitudes from AWAC 5-m sensor for top 3 depths
- AWAC 4 top layer measures show wide scatter relative to one another





Summary: COHrad – CORrad comparison, plans:

- COHrad radial velocity output file
  - can be summed for currents, processed for directional wave spectra
  - U.S. NTIA initial review passed for ONR Rivet Experiment
  - COHrads will not be produced in future due to expense of NTIA testing each mod
- CORrad unfiltered can be summed for currents
  - Radial striping presented a problem for 3D-FFT processing
  - Filtering removes striping – final solution is in hardware improvements
- New CORrad design completed, in testing
  - 16-bit A/D card at 150 MHz Maximum
  - Azimuth, pulses/rot counters now generated in Radar Control Box (RCB), not A/D card
  - IF used signal for both video and radial velocity
  - Standard Radar Video output still an option for user - Log power output

Finis

- Thank you for your attention
- Questions/comments??