# Application of Broadband/Wideband Technologies to Fisheries Acoustics

Dezhang Chu

NOAA/NMFS/NWFSC/FRAMD, 2725 Montlake Blvd. E., Seattle, WA 98112, USA

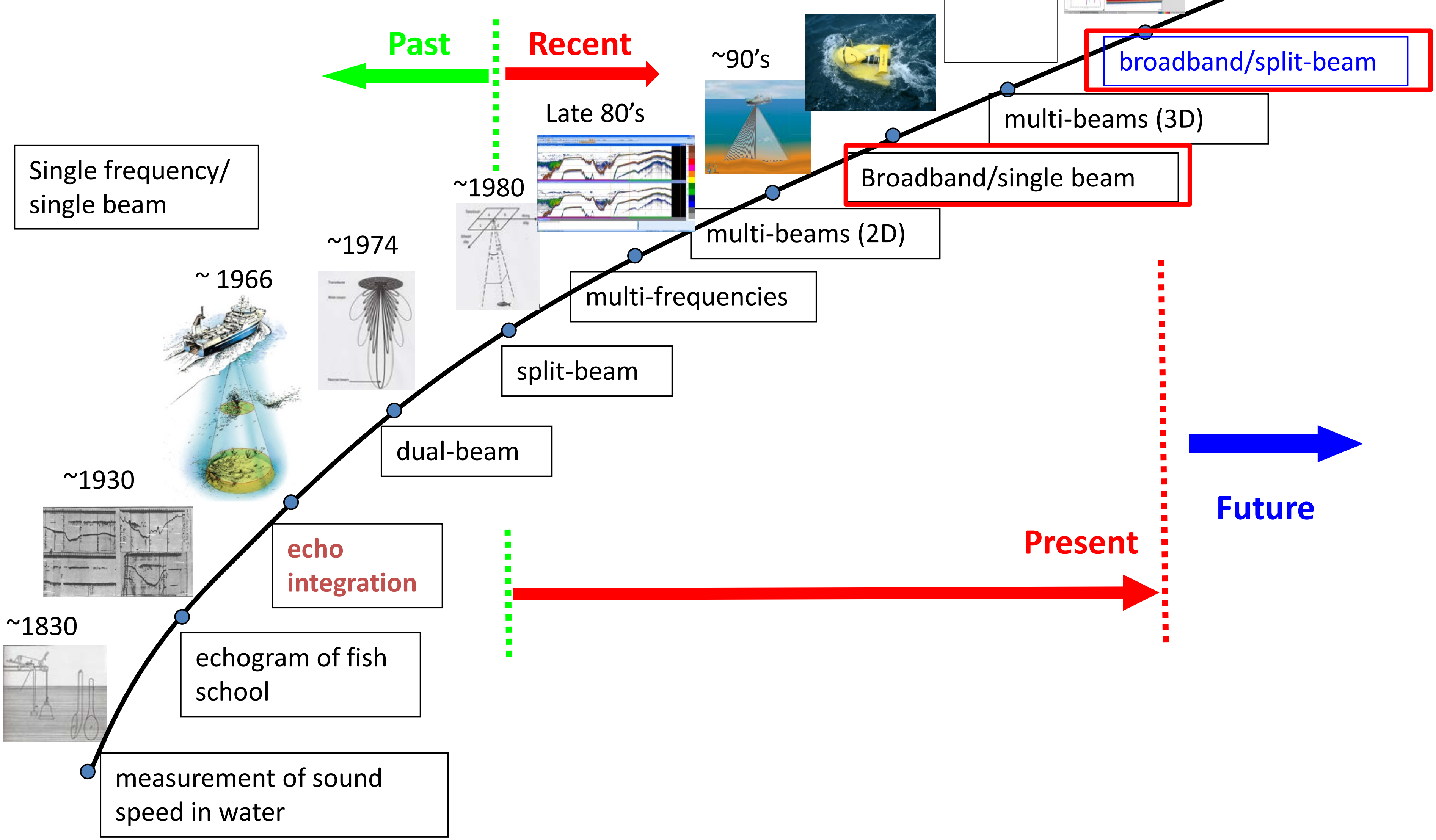
NOAA FISHERIES
NATIONAL MARINE FISHERIES SERVICE

NWFSC
NORTHWEST FISHERIES SCIENCE CENTER

# Outlines

- Introduction
- Theoretical Background
- Broadband/wideband Systems
- Application
- Summary

# Timeline of Technology Advances in Fisheries Acoustics



# Broadband/Wideband Systems

- EdgeTech System (signal beam)
  - 1-12 kHz, 4-24 kHz, 45-105 kHz, 160-270 kHz, 220-330 kHz, 330-470 kHz, 450-590 kHz
- Simrad System – EK80 (split-beam)
  - 32-45 kHz, 50-90 kHz, 90-160 kHz, 160-250 kHz, 250-450 kHz
- Simrad System – SN90 (Multi-beam)

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# Acoustic signals

## Complex signal:

Amplitude (real)

$$f(t) = A(t)\, e^{i\phi(t)}$$

Phase (real)

## Complex conjugate signal:

$$f^*(t) = A(t)\, e^{-i\phi(t)}$$

## Real and imaginary components:

$$f_R(t) = \mathrm{Re}(f(t))$$
$$f_I(t) = \mathrm{Im}(f(t))$$

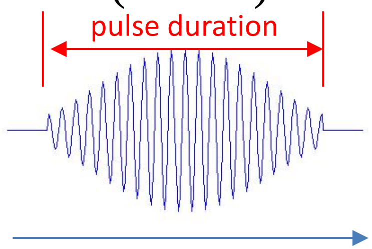
$$\Longrightarrow \quad f(t)\, f^*(t) = A^2(t) = \left| f_R(t) \right|^2 + \left| f_I(t) \right|^2$$

# Representations of an acoustic wave

$$\psi(t/c-r) \longrightarrow \psi[k(t/c-r)] = \psi(\omega t - kr)$$

Temporal Representation

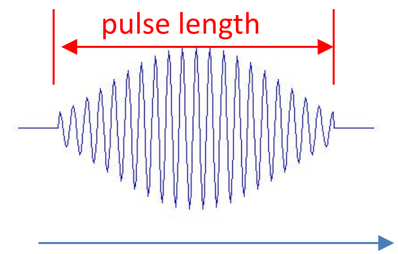
(fixed $r$)




Time

Spatial Representation

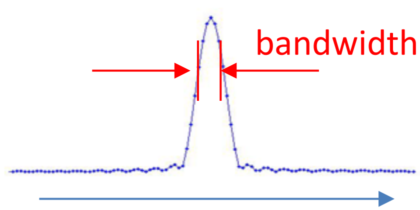
(fixed $t$)




Range

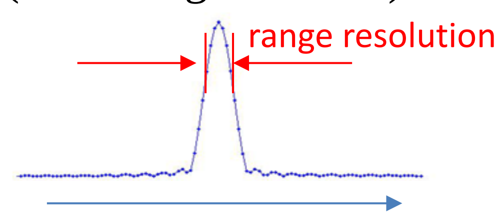
Spectral Representation

(fixed time window)



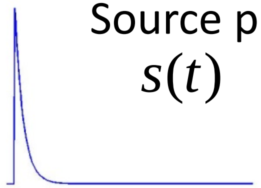

Frequency

(fixed range window)

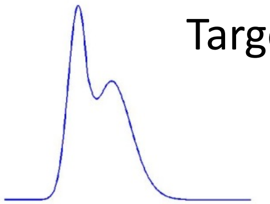



wavenumber

# Convolution & Correlation – Time domain



Source pulse
$s(t)$

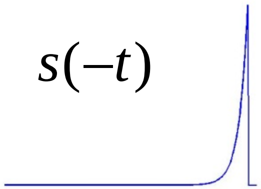


Target Impulse response
$f(t)$

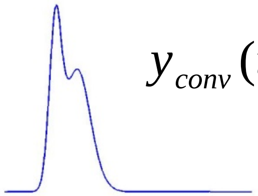
**Convolution:**

$$y_{conv}(t) = s(t) * f(t)$$

$s(-t)$



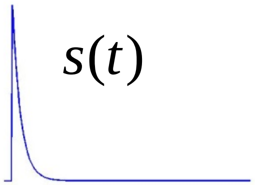
$$y_{conv}(t) = \int s(t-\tau) f(\tau) d\tau$$



$y_{conv}(t)$

**Correlation:**

$$y_{corr}(t) = s(t) \otimes f(t)$$



$s(t)$

$$y_{corr}(t) = \int s(\tau - t) f(\tau) d\tau$$

$y_{corr}(t)$

# Convolution & Correlation – Frequency Domain

$$s(t) \Leftrightarrow S(f) \qquad f(t) \Leftrightarrow F(f)$$

**Convolution:**

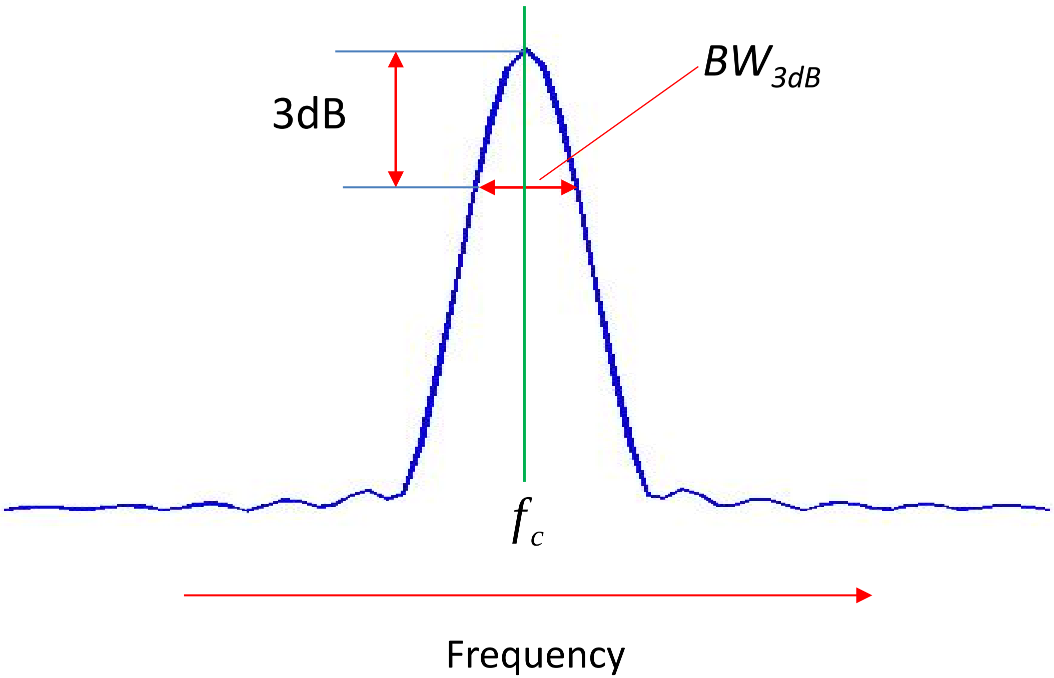
$$y_{conv}(t) = s(t) * f(t) = f(t) * s(t) \Rightarrow Y_{conv}(f) = S(f)F(f)$$

**Correlation:**

$$y_{corr}(t) = s(t) \otimes f(t) \Rightarrow S(-f)F(f) \underset{\text{real } s(t)}{=} S^*(f)F(f)$$

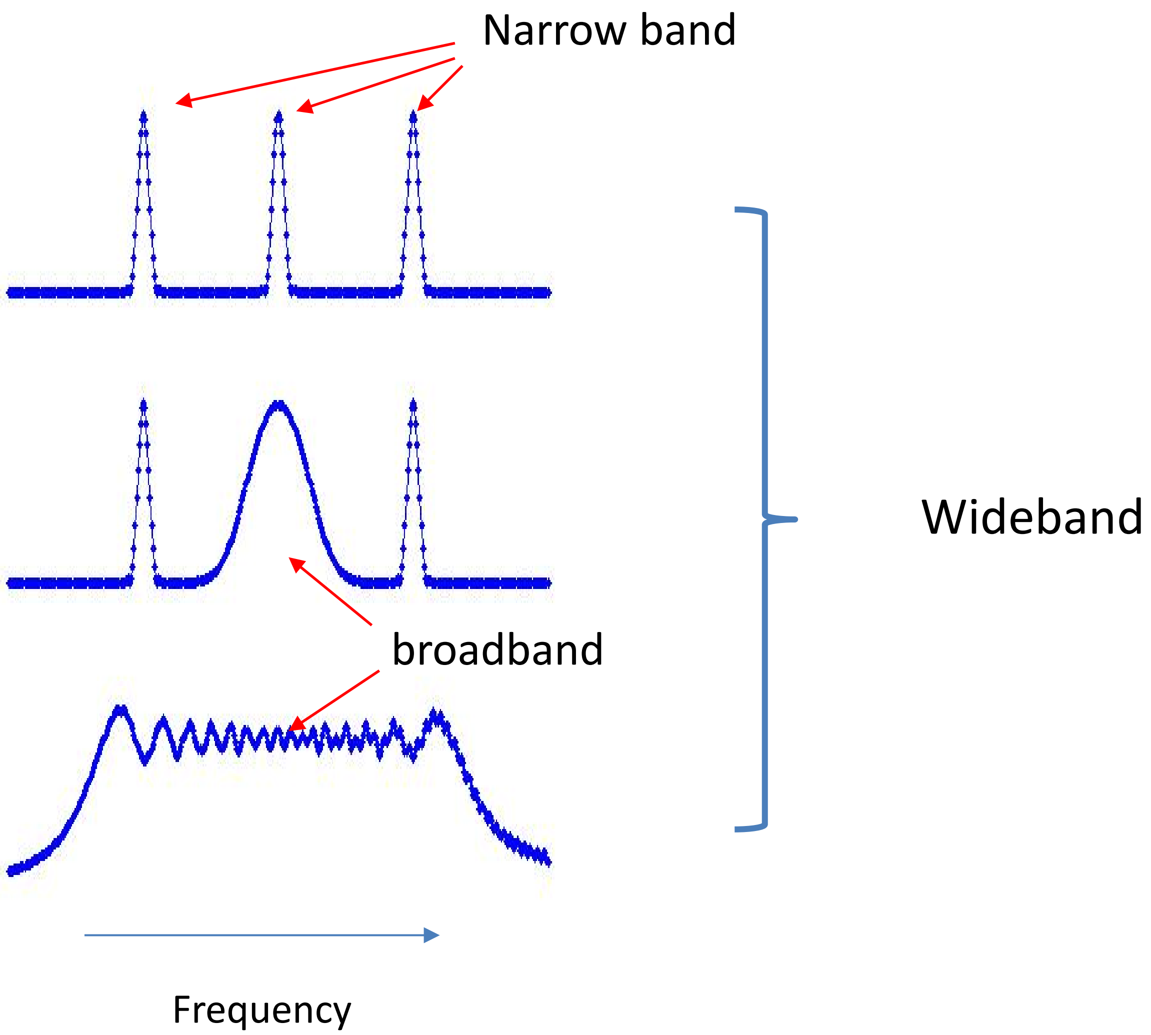
$$y_{corr}(t) = f(t) \otimes s(t) \Rightarrow S(f)F(-f) \underset{\text{real } f(t)}{=} S(f)F^*(f)$$

# Narrow Band/Broadband Signals



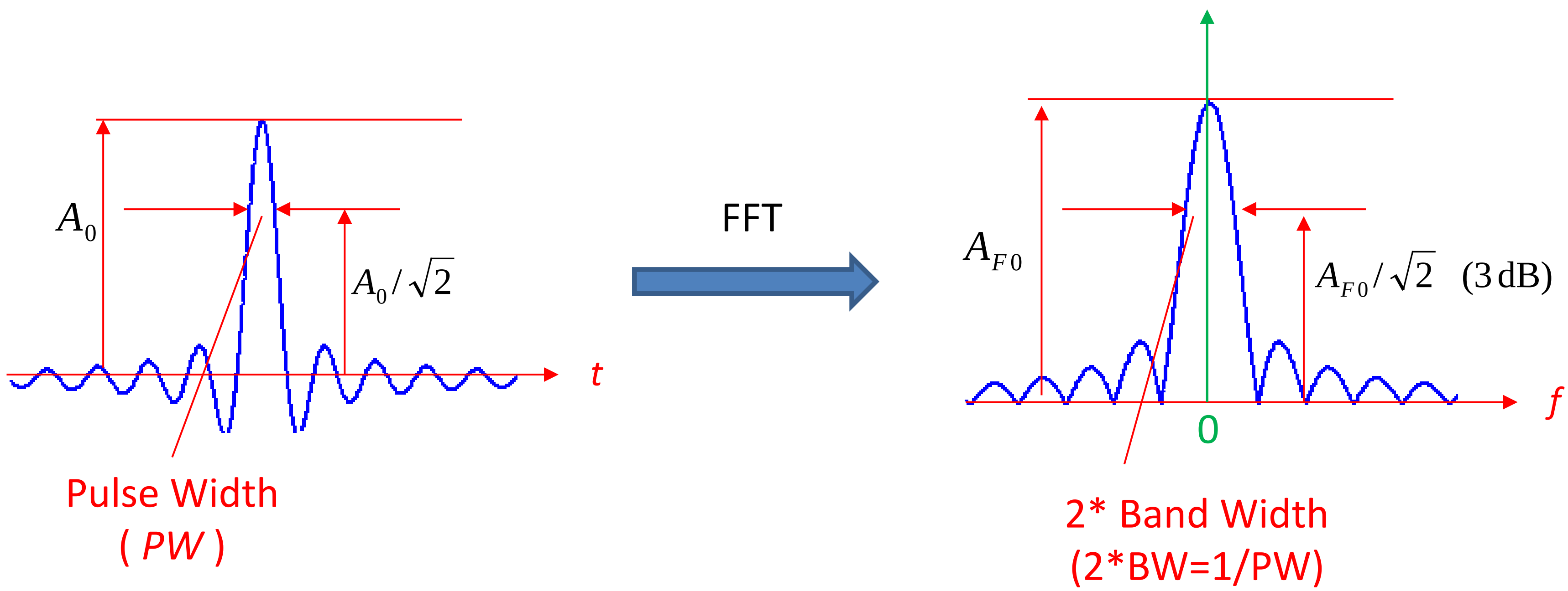

$$Q = \frac{f_c}{BW_{3dB}} \Rightarrow \begin{cases} >10 & \text{narrow band} \\ \text{in between} & ?? \\ <3 & \text{broadband} \end{cases}$$

# Broadband/Wideband Signals



# Broadband signals - 1

## Short pulse



# Broadband signals - 2

## Frequency-modulated signals

$$f(t) = \frac{\omega(t)}{2\pi} = \frac{1}{2\pi}\frac{d}{dt}\phi(t) = \begin{cases} f_0 & \text{CW} \\ f_0 + \alpha\, t & \text{linear chirp} \\ \beta\, \Phi(t) & \text{nonlinear chirp} \end{cases}$$

with

$\alpha$ and $\beta$ are constants

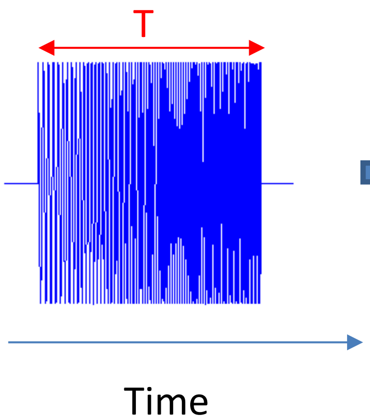
$t_0 \le t \le t_0 + T$

$f_0$ is the frequency at $t = t_0$

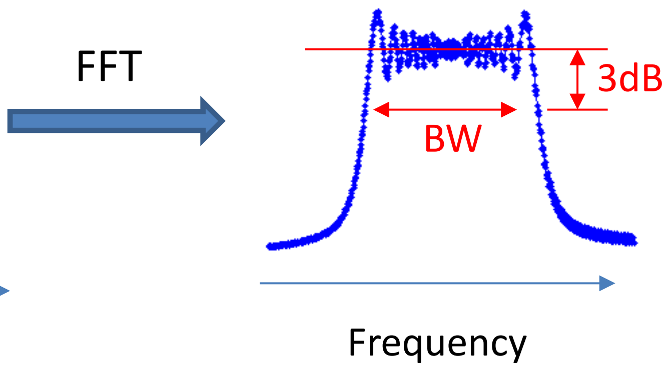
Linear-Frequency-Modulated Signal (LFMS): $$\alpha = \frac{f_0 \pm BW}{2T}$$

up-chirp example:

$$\alpha = \frac{f_0 + BW}{2T}$$




FFT



# Matched Filter/Pulse Compression- 1

Representation of a time series:

$$x(t) = s(t) + n(t)$$

$s(t)$: signal
$n(t)$: noise

A filter, $a(t)$, is applied to the time series $x(t)$:

$$y(t) = x(t) * a(t) = s(t) * a(t) + n(t) * a(t)$$

The ratio of the instantaneous power of the signal to that of the noise at time $\tau$ is

$$\Gamma(\tau) = \frac{\left(\int_0^\tau a(t) s(\tau - t)\, dt\right)^2}{\left(\int_0^\tau a(t) n(\tau - t)\, dt\right)^2}$$

# Matched Filter/Pulse Compression- 2

Maximizing the above equation with respect to $a(t)$ leads to

$$a(t) = k\, s(\tau - t)$$

i.e., a filter ***Matched*** to the original signal, and is called ***Matched Filter*** (MF), and also called the ***replica*** of the original signal $x(t)$. Since $\tau$ is merely a time shift, without loss of generality, we can express the replica or matched filter as $a(t) = k\, s(-t)$.

# Matched Filter/Pulse Compression- 3

We have

$$s(t) * a(t) = ks(t) * s(-t) = ks(t) \otimes s(t) = kr_{ss}(t)$$

$$n(t) * a(t) = kn(t) * s(-t) = kn(t) \otimes s(t) = kr_{ns}(t)$$

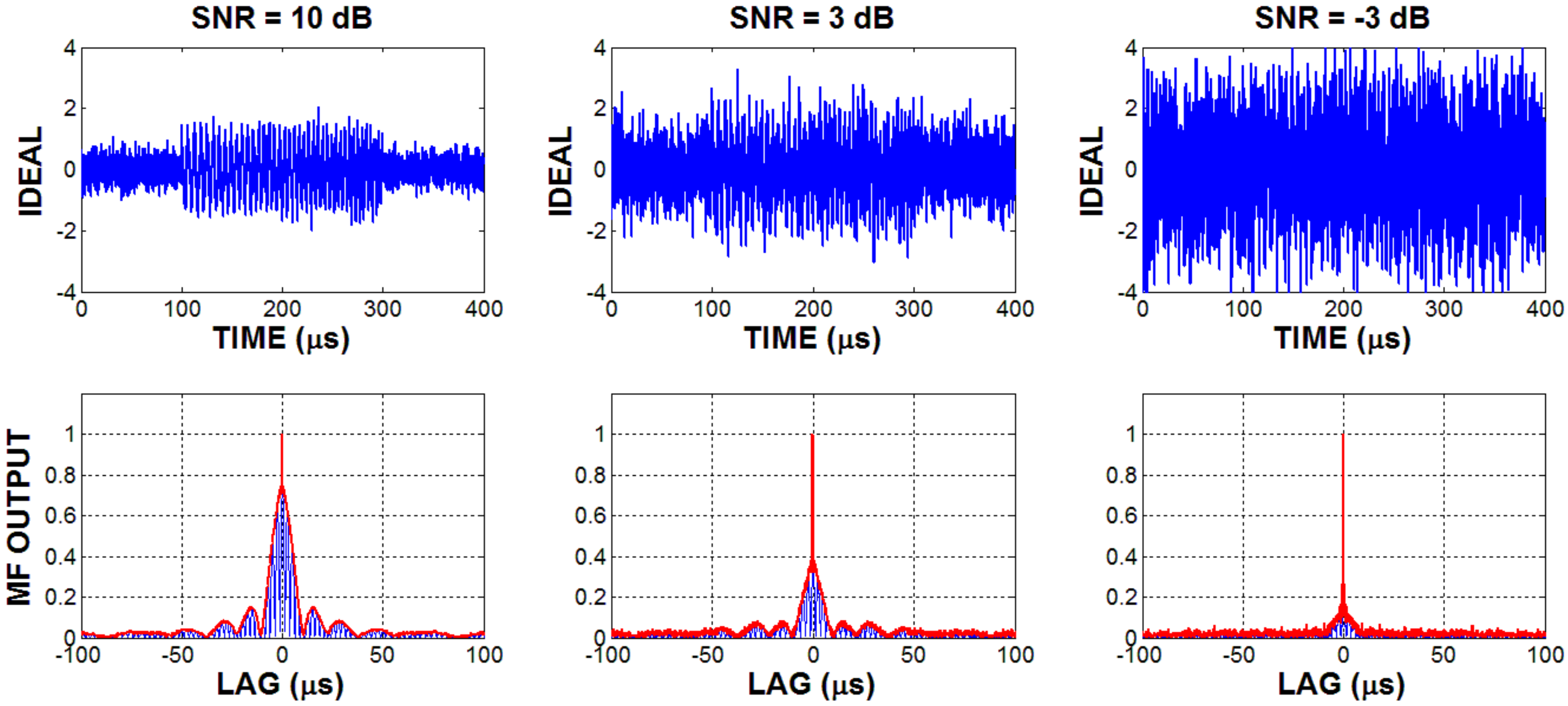
Hence

$$y(t) = k\, r_{ss}(t) + k\, r_{ns}(t)$$

where $r_{ss}(t)$ is the auto-correlation function of the signal and $r_{ns}(t)$ is the cross-correlation function of the noise and the signal, which approaches to zero for a white noise, i.e. $r_{ss}(t) >> r_{ns}(t)$.

# Matched Filter/Pulse Compression- 4

## MF output for different Signal-to-Noise Ratios (SNR):

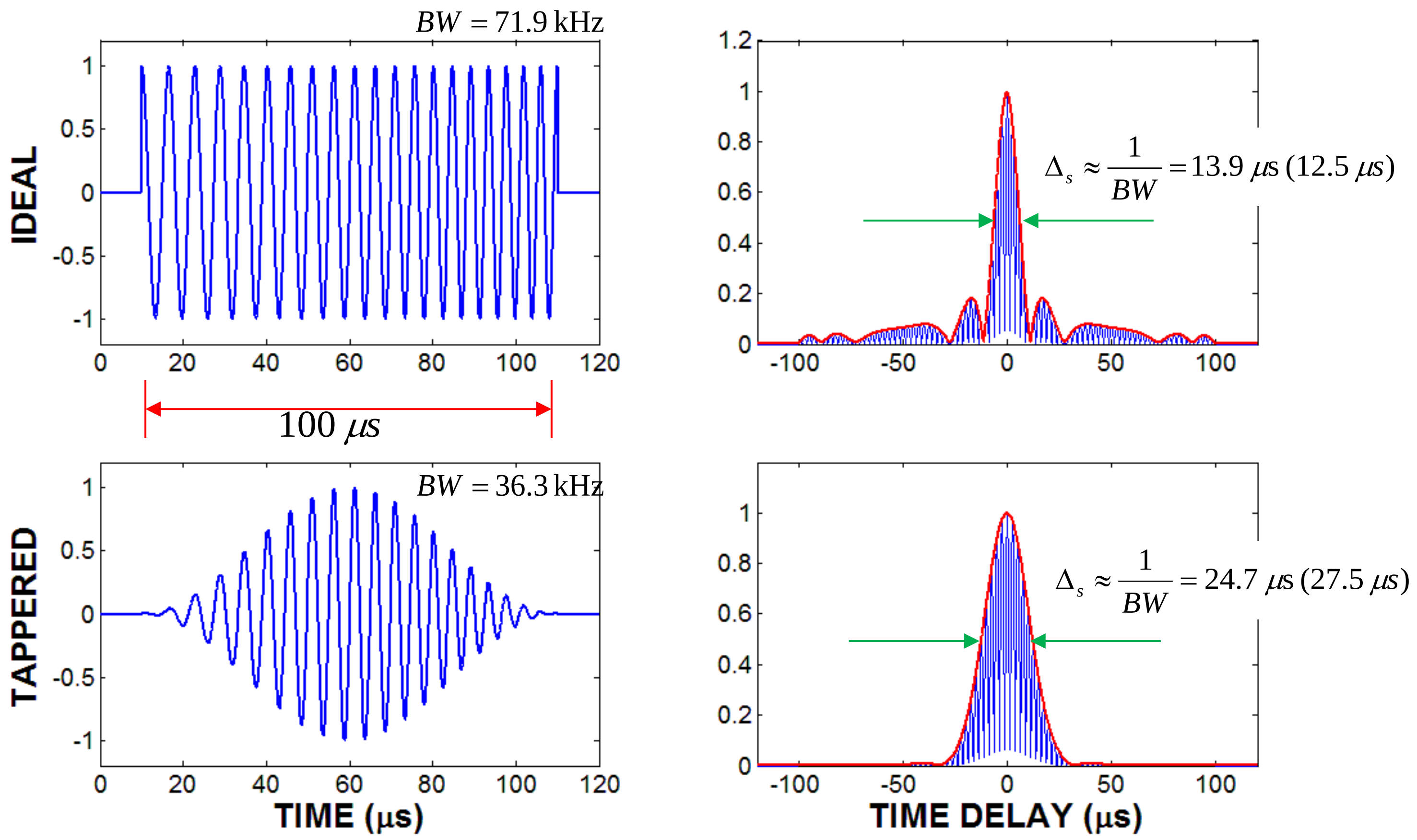



MF Gain = 2BT

B = Bandwidth
T = Pulse duration

# Matched Filter/Pulse Compression- 5

Temporal resolution resulting from MF process:



# Scattering Application- 1

## Generic scattering process:

$$y_{scat}(t) = s_0(t) * h(t) * f_{scat}(t) + n(t) = s_{eff}(t) * f_{scat}(t) + n(t)$$

$s_0(t)$: transmit electric signal (source)

$h(t)$: system response including transducer, spreading, attenuation, etc

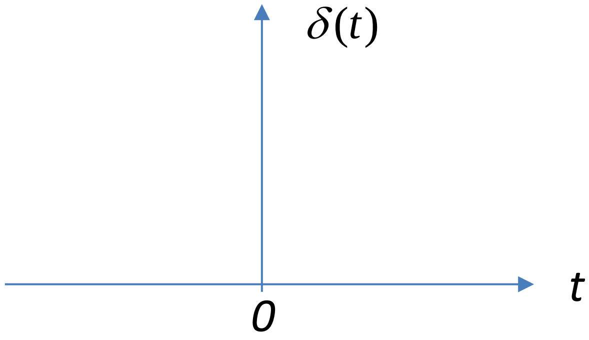
$f_{scat}(t)$: impulse response of the target

$s_{eff}(t)$: effective source (incident wave)

## For a broadband system

$$h(t) \sim \delta(t) = \begin{cases} \infty & t = 0 \\ 0 & t \neq 0 \end{cases}$$

where $\delta$(t) is a Dirac delta function



# Scattering Application- 2

$$y_{conv}(t) = \underbrace{s_0(t) * h(t)}_{s_{eff}(t)} * f_{scat}(t) + n(t) = s_{eff}(t) * f_{scat}(t) + n(t)$$

The true Matched Filter (MF) needed to best characterize the scattering function $f_{scat}(t)$ should be $s_{eff}(t)$. However, since $h(t)$ is generally unknown, we normally use $ks_0(t)$ as the replica of the PC processing:

$$\begin{aligned} y_{MF}(t) &= ks_0(t) \otimes y_{scat}(t) = ks_0(t) \otimes \left(s_0(t) * h(t) * f_{scat} + n(t)\right) \\ &= ks_0(t) \otimes s_0 * h(t) * f_{scat}(t) + ks_0(t) \otimes n(t) \\ &= kr_{ss}(t) * h(t) * f_{scat}(t) + kr_{ns}(t) \end{aligned}$$

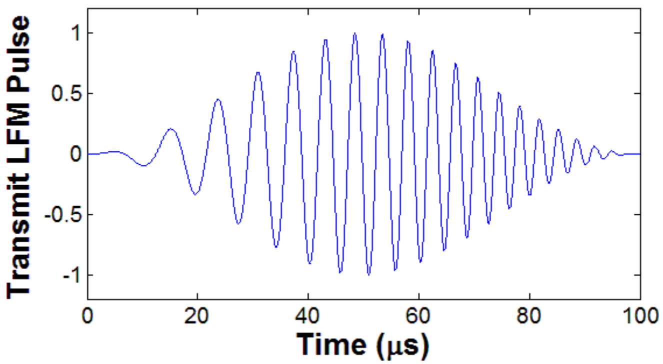
# Scattering Application- 3

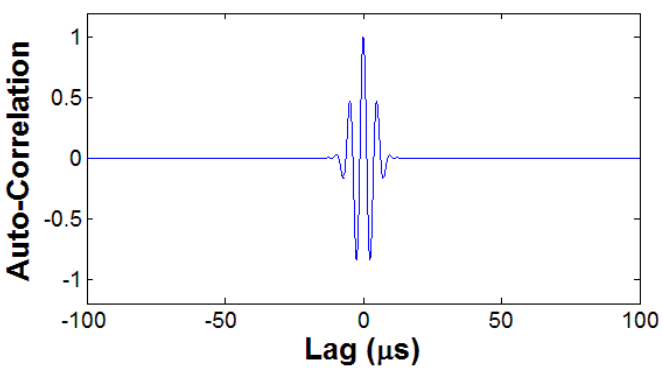
For $h(t) \sim \delta(t)$, the output of MF, $y_{MF}(t)$, or more appropriately, Pulse Compression, $y_{PC}(t)$ , can characterize the impulse response of the scattering by a target or targets:

$$
\begin{aligned}
y_{PC} &= kr_{ss}(t) * h(t) * f_{scat}(t) \\
&\approx kr_{ss}(t) * f_{scat}(t)
\end{aligned}
$$

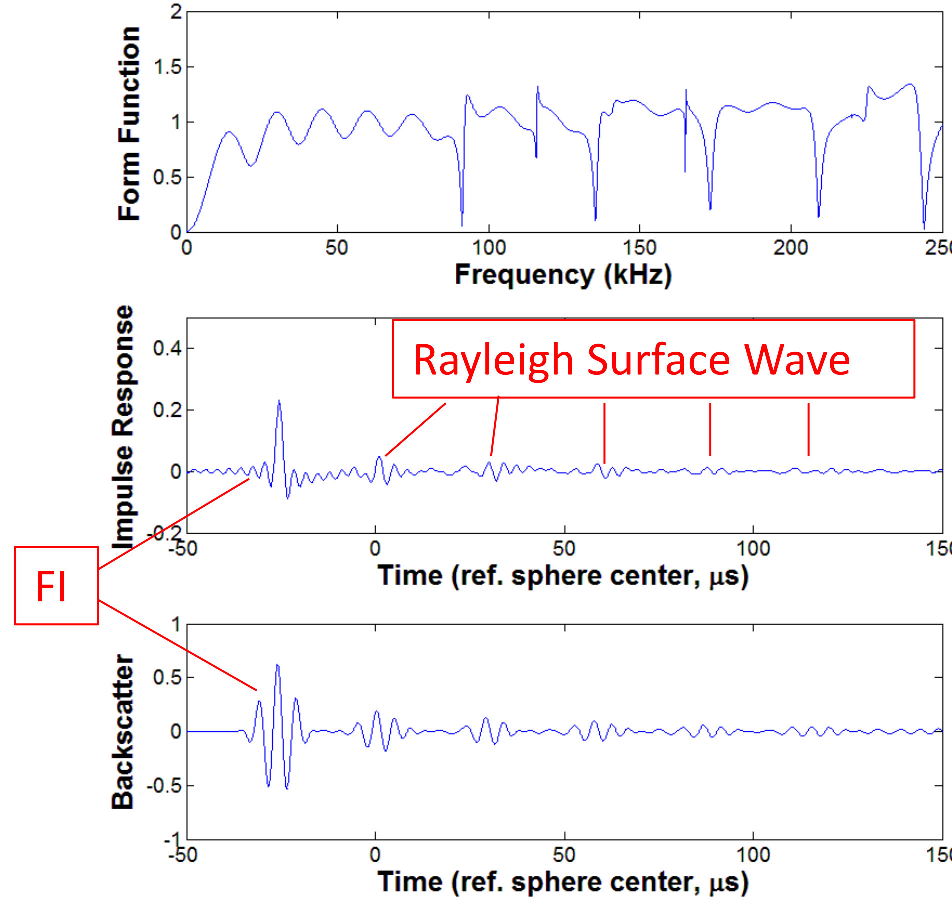
# Backscattering by an elastic sphere

## Frequency: 150-250 kHz




## WC38.1



# Calibration - 1 (Target Strength)

Recall that the scattering by an object with PC processing:

$$y_{PC}(t) = r_{ss}(t) * h(t) * f_{scat}(t) + r_{ns}(t)$$

$r_{ns}(t)$ is the scattering by noise and unwanted signals that can be ignored in time domain. The system response, $H(f)$, (in frequency domain)

$$H(f) = \frac{Y_{PC}(f)}{S(-f)S(f)F_{scat}(f)}$$

Frequency response of the received signal after PC processing

Source function

Back scattering by calibration sphere

# Calibration - 2 (Volume Scattering)

For computing the volume backscattering, $S_v$, there are more parameters need to be determined. The backscattered signal from *N* targets within a volume after pulse-compression can be expressed as

$$y_{PC}^{\Sigma}(t) = r_{ss}(t) * h(t) * \sum_{k=1}^{N} f_{scat}^{k}(t)$$

where $f_{scat}^{k}(t)$ is the backscattering impulse response of the *k*th target.

Corresponding representation of the above equation in frequency domain is

$$Y_{PC}^{\Sigma}(f) = R_{ss}(f)H(f)\sum_{k=1}^{N} F_{scat}^{k}(f)$$

Assuming the target uniformly distributed within the sample volume, the *incoherent summation* of the scattered signal is then

$$s_{v}^{\Sigma}(f) = Y_{v}^{\Sigma}(f)Y_{v}^{\Sigma*}(f) = \left|R_{ss}(f)H(f)\right|^{2}\sum_{k=1}^{N}\sigma_{bs}^{k}(f)$$

where $\sigma_{bs}^{k}(f)$ is the differential backscattering cross section of *k*th target.

The incoherent summation term can be expressed as

$$\sum_{k=1}^{N} \sigma_{bs}^{k}(f) = V_s(f)\,\rho_v < \sigma_{scat}(f) >= V_s(f)\,s_v(f)$$

backscattering per unit volume

where $\rho_v$ is the number density of the target within the sample volume, $V_s(f)$, which is a function of frequency and can be expressed as:

$$V_s(f) = r^2\,\psi_{eq}(f)\frac{c\,\tau_{eff}}{2}$$

The equivalent 2-way beam angle $\psi_{eq}(f)$ is a function of frequency, and the effective pulse duration $\tau_{eff}$ is the width of the FFT in time domain without any tapering effect. The tapering or shading of the original chirp signal has been included in $R_{ss}(f)$.

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# EdgeTech Systems

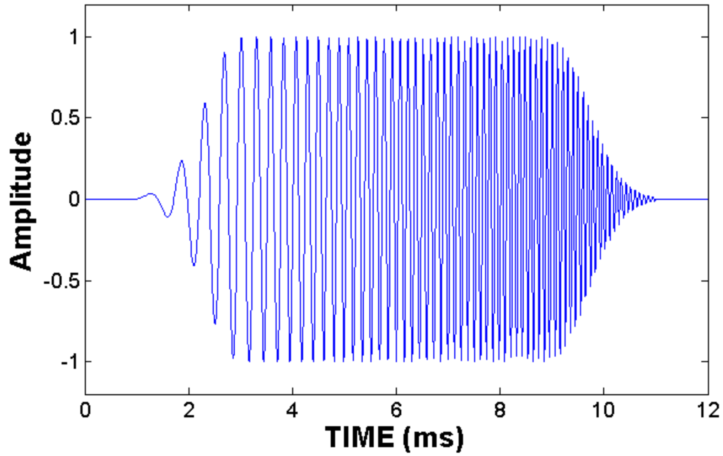
- Multi-frequency bands & signal beam
  - 1-12 kHz, 4-24 kHz, 45-105 kHz (towed system)
  - 160-270 kHz, 220-330 kHz, 330-470 kHz, 450-590 kHz (vertical deployable system)

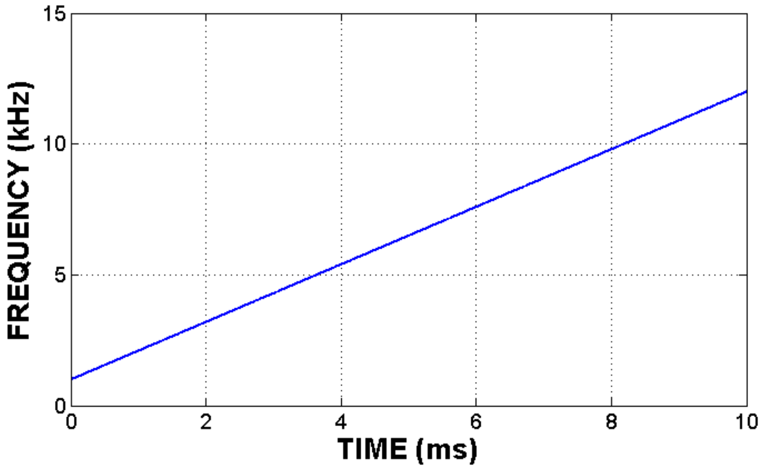
# Edgetech Chirp Signal

## Linear Frequency modulation

$$f(t) = \frac{\omega(t)}{2\pi} = \frac{1}{2\pi}\frac{d}{dt}\phi(t) = \upsilon + 2\alpha t$$

$$\begin{cases} f(0) = f_{start} \\ f(T) = f_{stop} \end{cases} \Rightarrow \begin{cases} \upsilon = f_{start} \\ \alpha = \dfrac{f_{stop} - f_{start}}{2T} \end{cases}$$



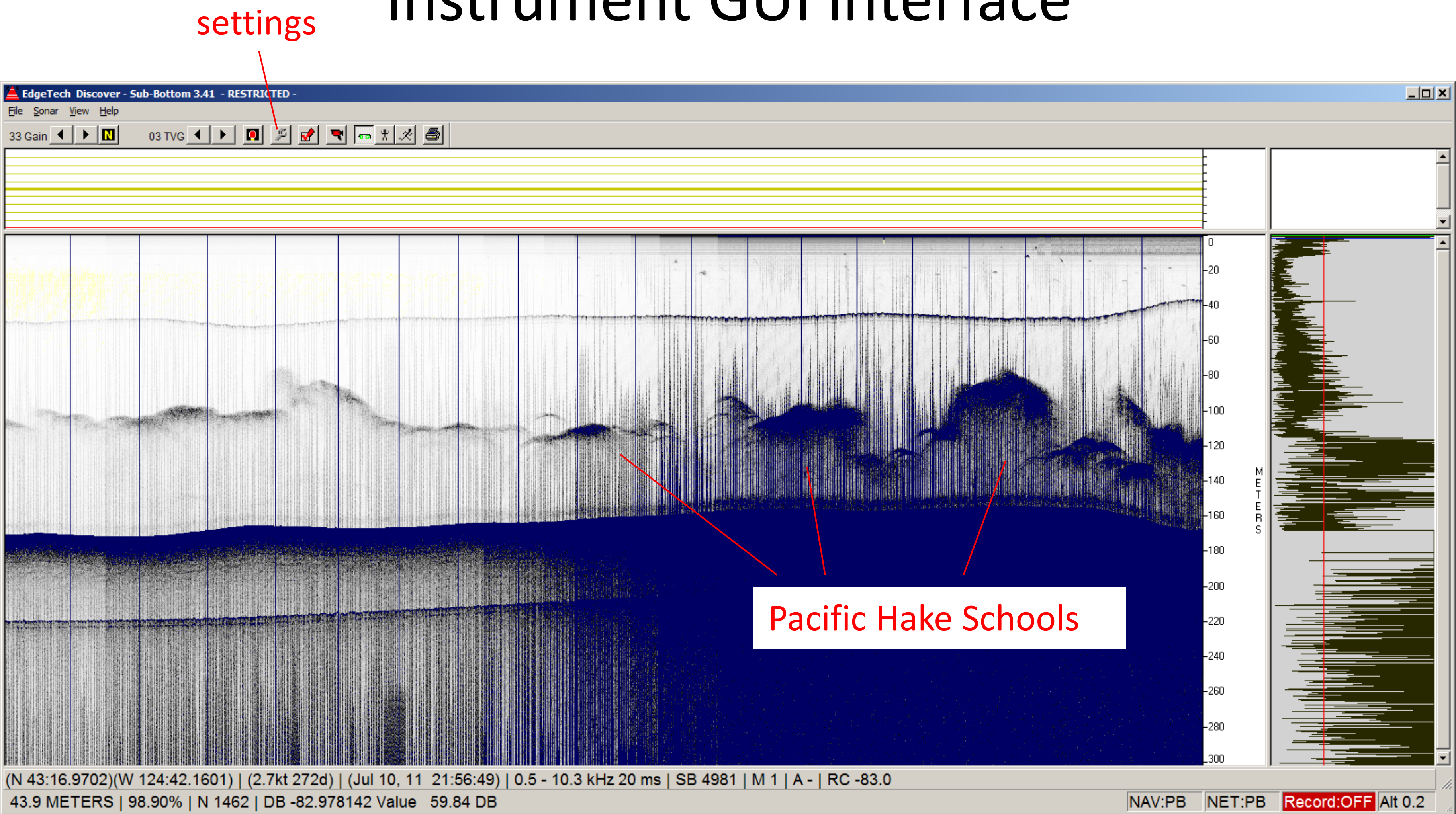
Pros:

- Arbitrary pulse shape
- Frequency band, duration, shading (tapering) are configurable
- Lower frequency band, capable of covering fish resonance frequency

Cons:

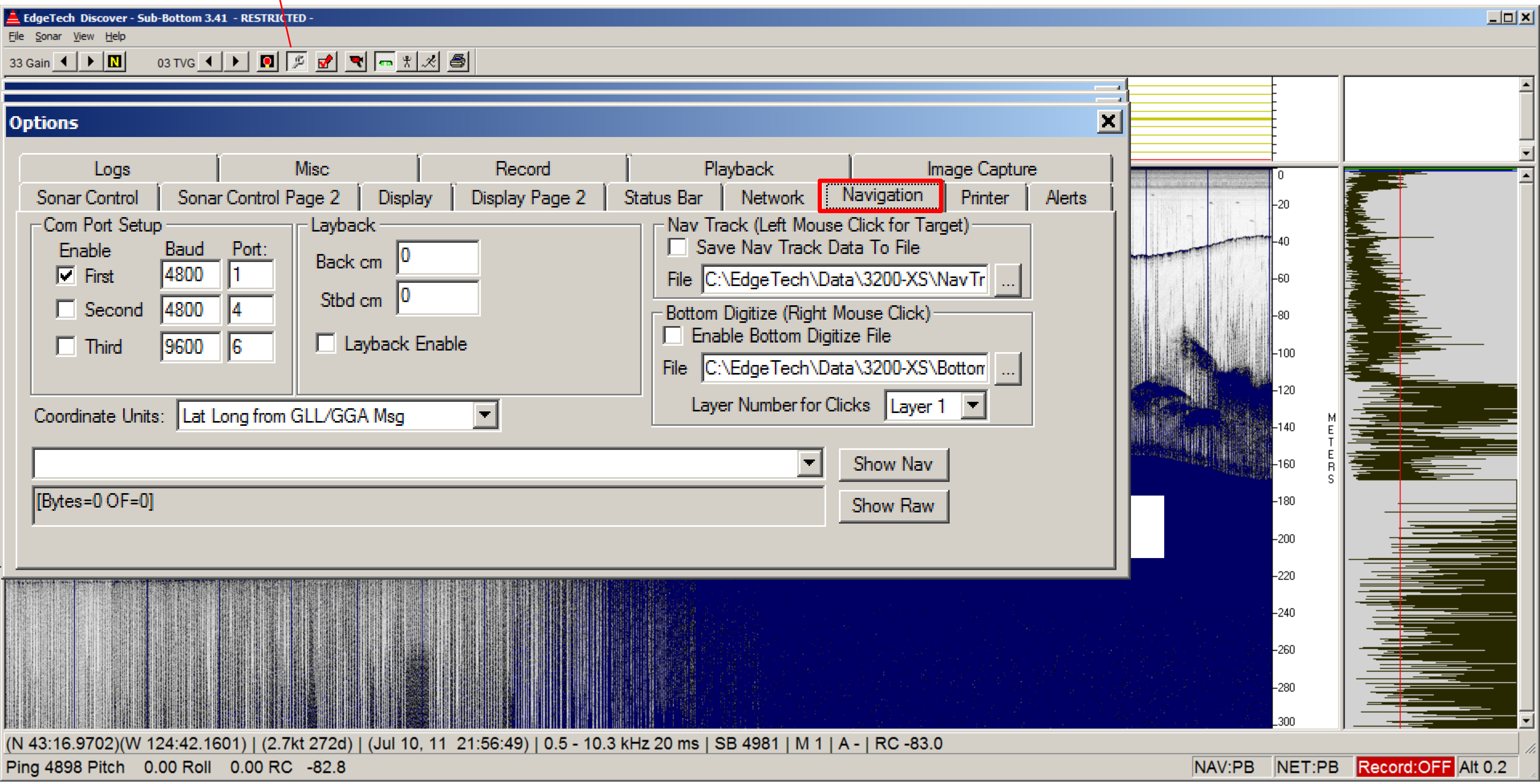
- Single beam - difficult to conduct calibration  and TS measurements
- Can’t be mounted on vessels easily

# Instrument GUI interface



# Instrument GUI interface

settings



# Simrad System – EK80

- Multi-frequency bands & Split-beam system
  - 32-45 kHz, 50-90 kHz, 90-160 kHz, 160-250 kHz, 250-450 kHz

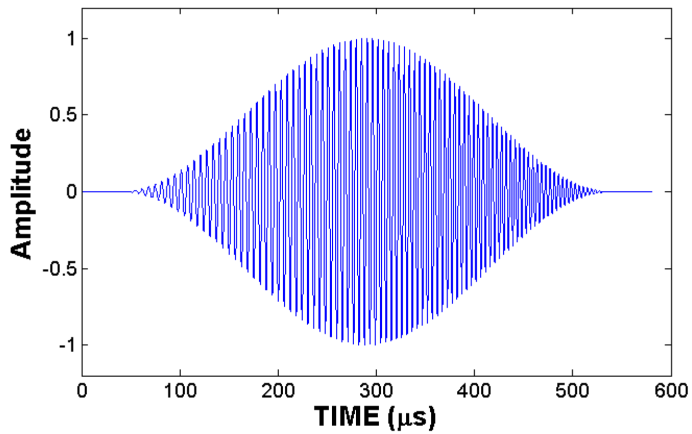

can be configured as broadband or narrow band application

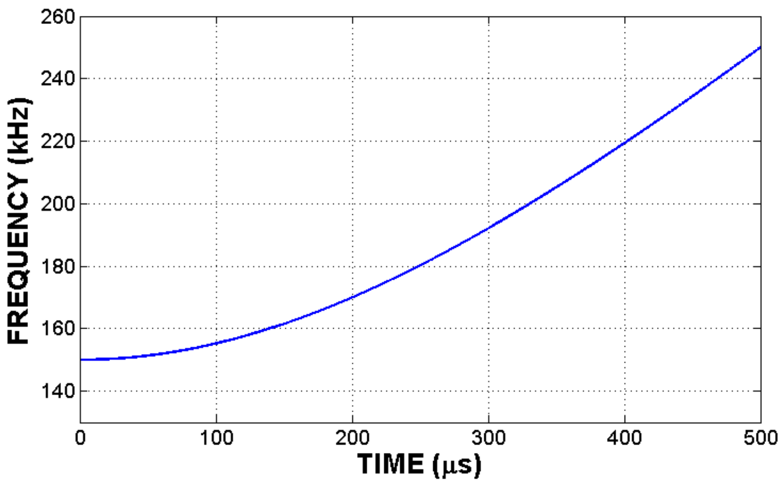
# Simrad EK80 Chirp Signal

## Hyperbolic Frequency modulation

$$f(t) = \frac{\omega(t)}{2\pi} = \frac{1}{2\pi}\frac{d}{dt}\phi(t) = \beta\sqrt{1+\gamma t^2}$$

$$\begin{cases} f(0) = f_{start} \\ f(T) = f_{stop} \end{cases} \Rightarrow \begin{cases} \beta = f_{start} \\ \gamma = \dfrac{\left(f_{stop} / f_{start}\right)^2 - 1}{T^2} \end{cases}$$



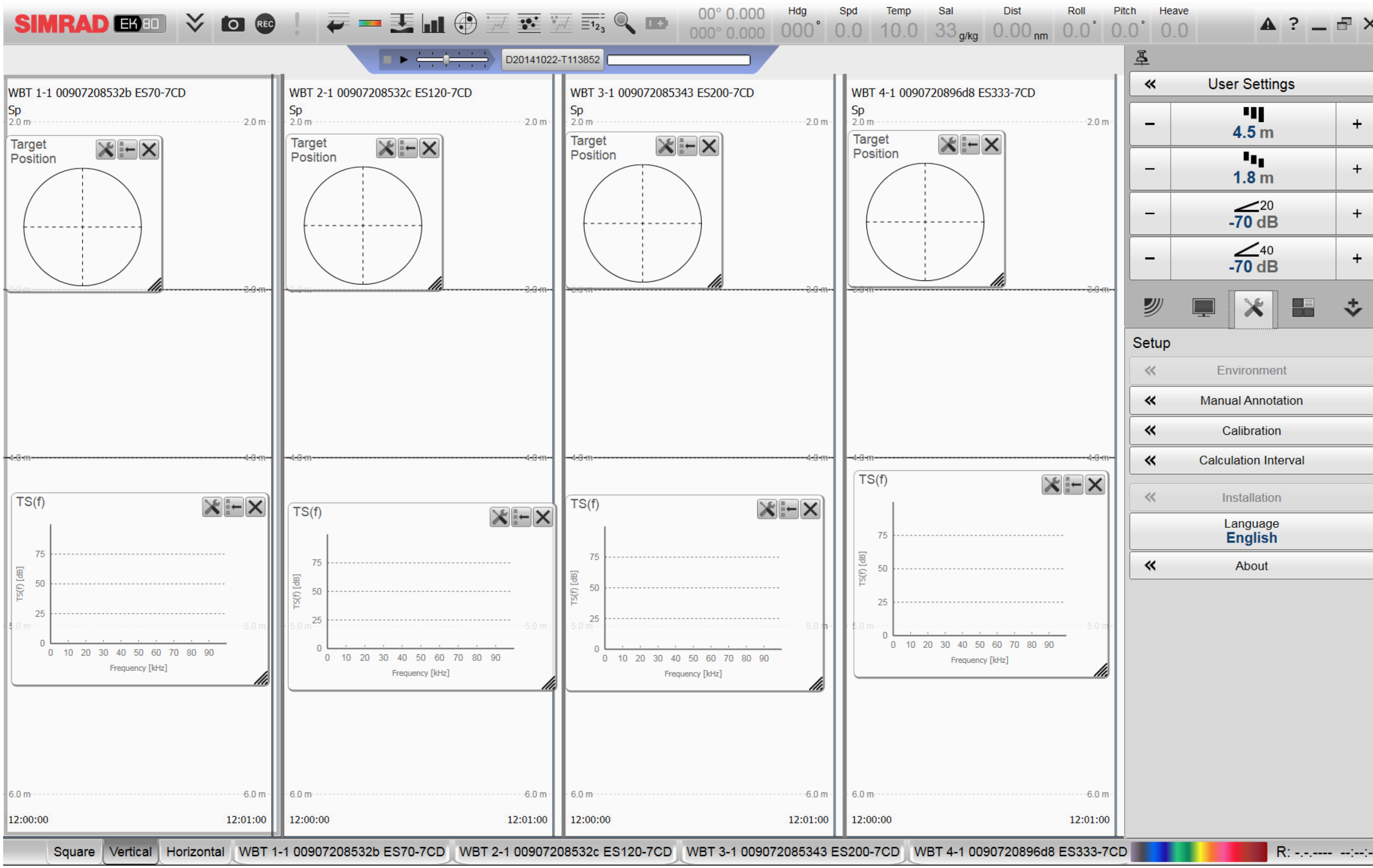
## Pros:

- Frequency band and duration are configurable (can be CW)
- Tapering function is selectable
- Split-beam complex data – easy for system calibration and TS measurements

## Cons:

- Pulse shape and shading function are less flexible
- Frequency bands are all much higher than fish resonance frequencies

# Instrument GUI interface



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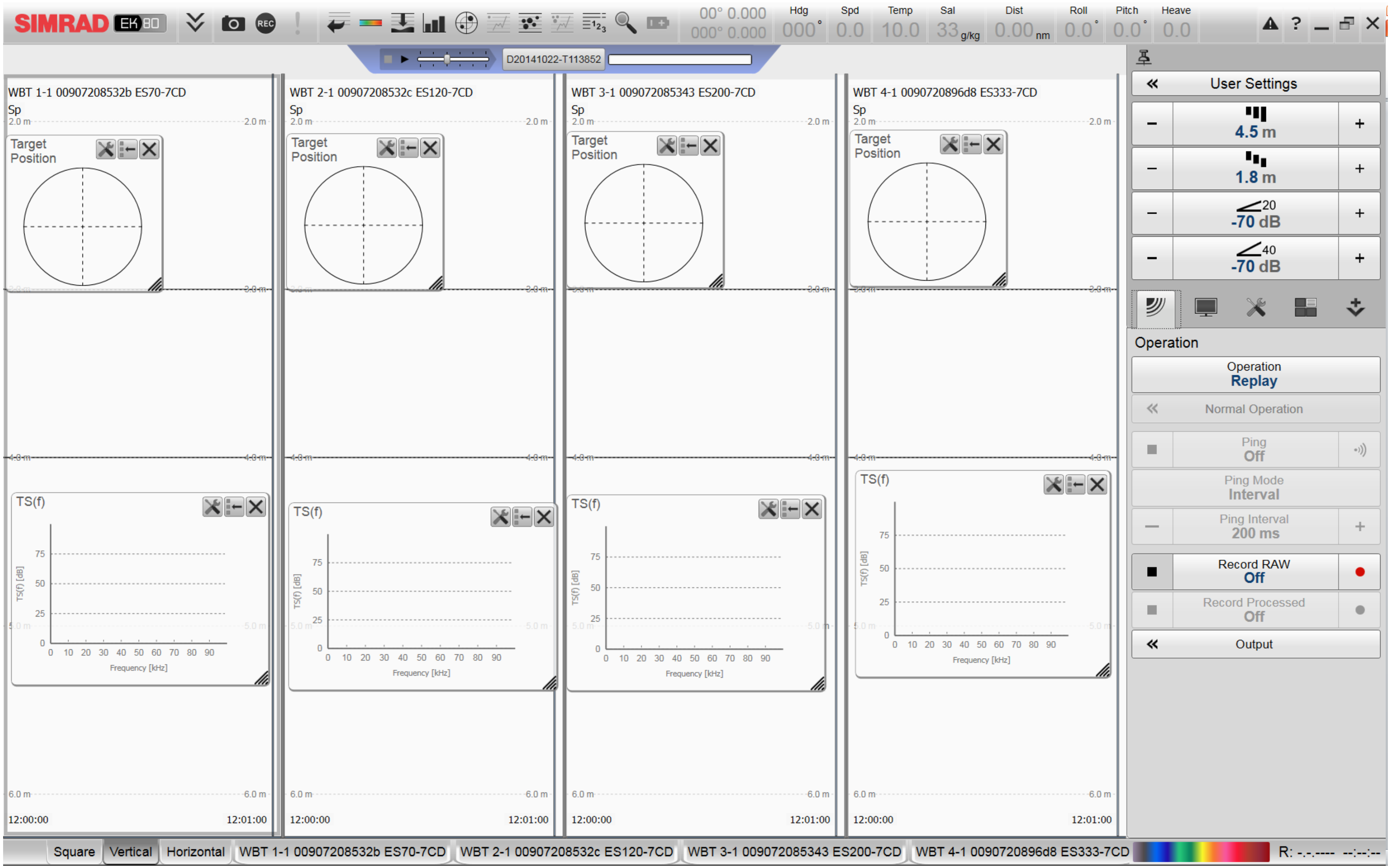

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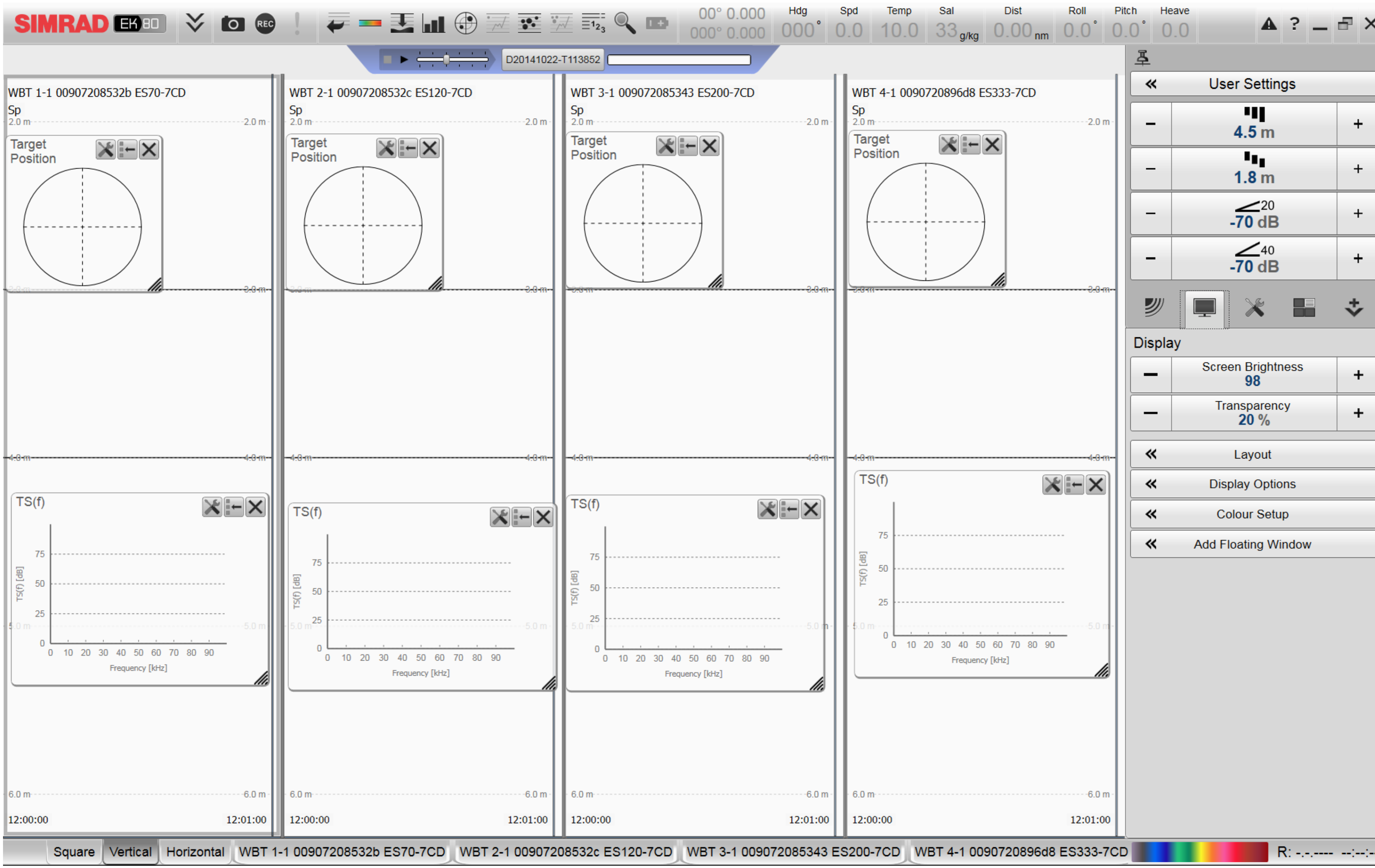

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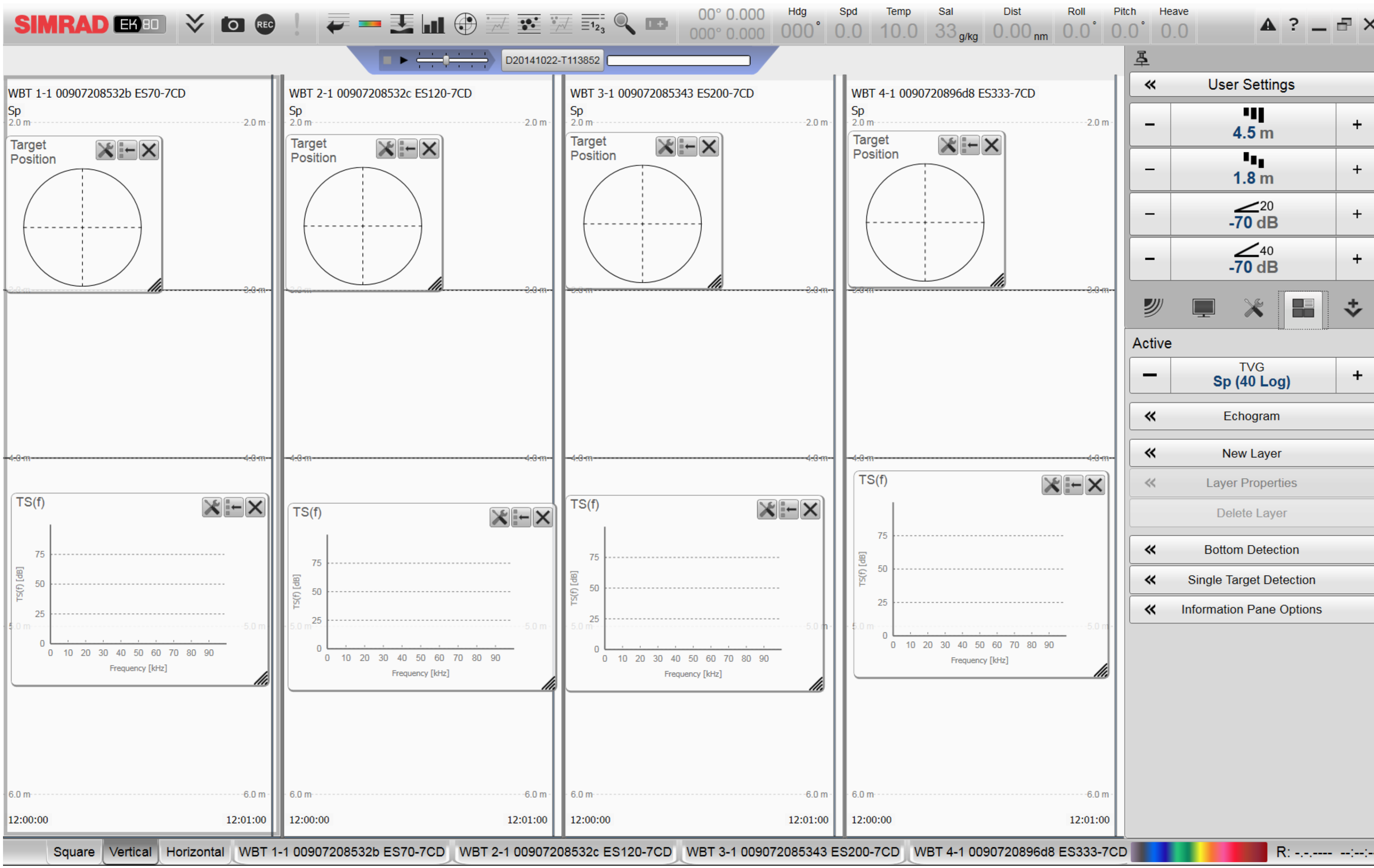
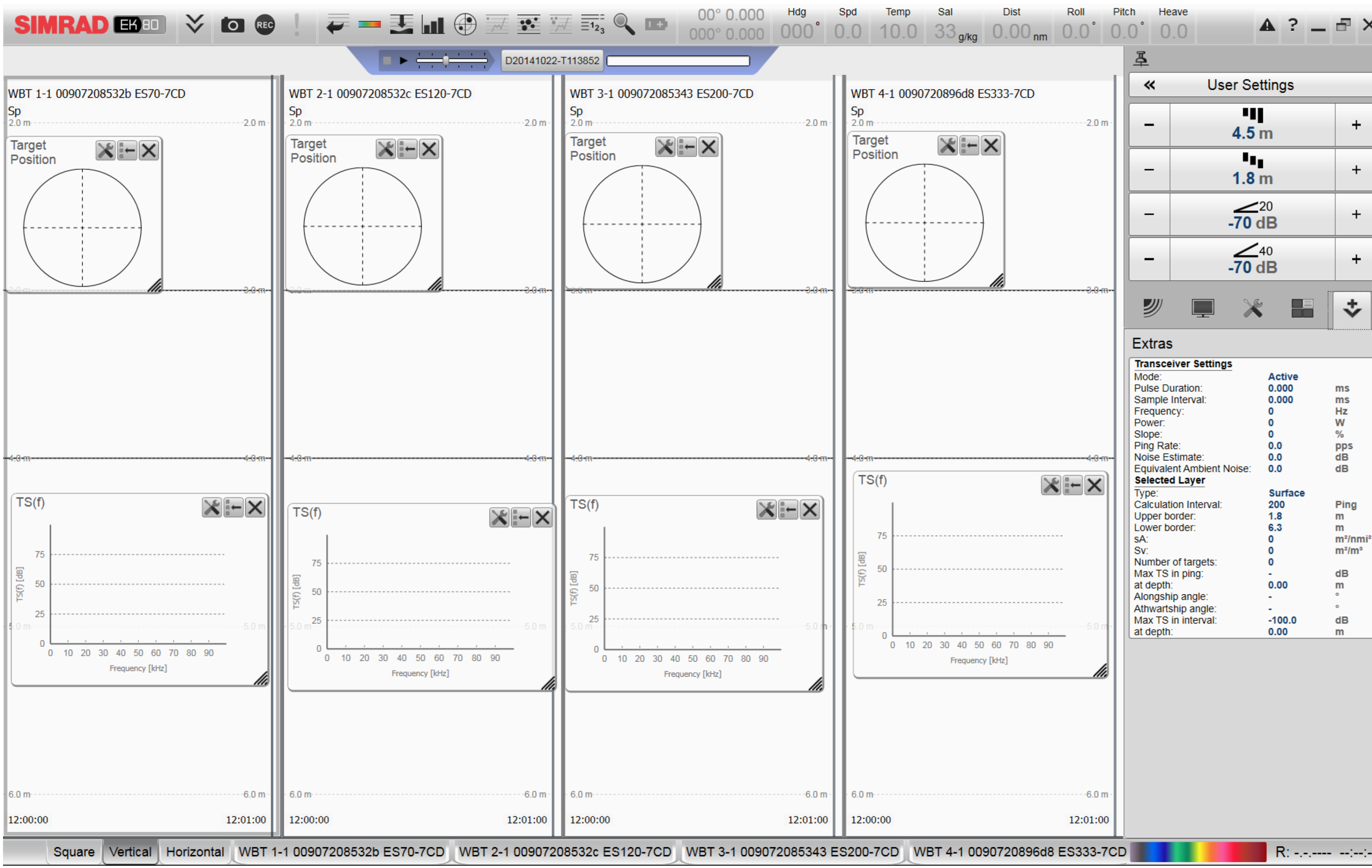
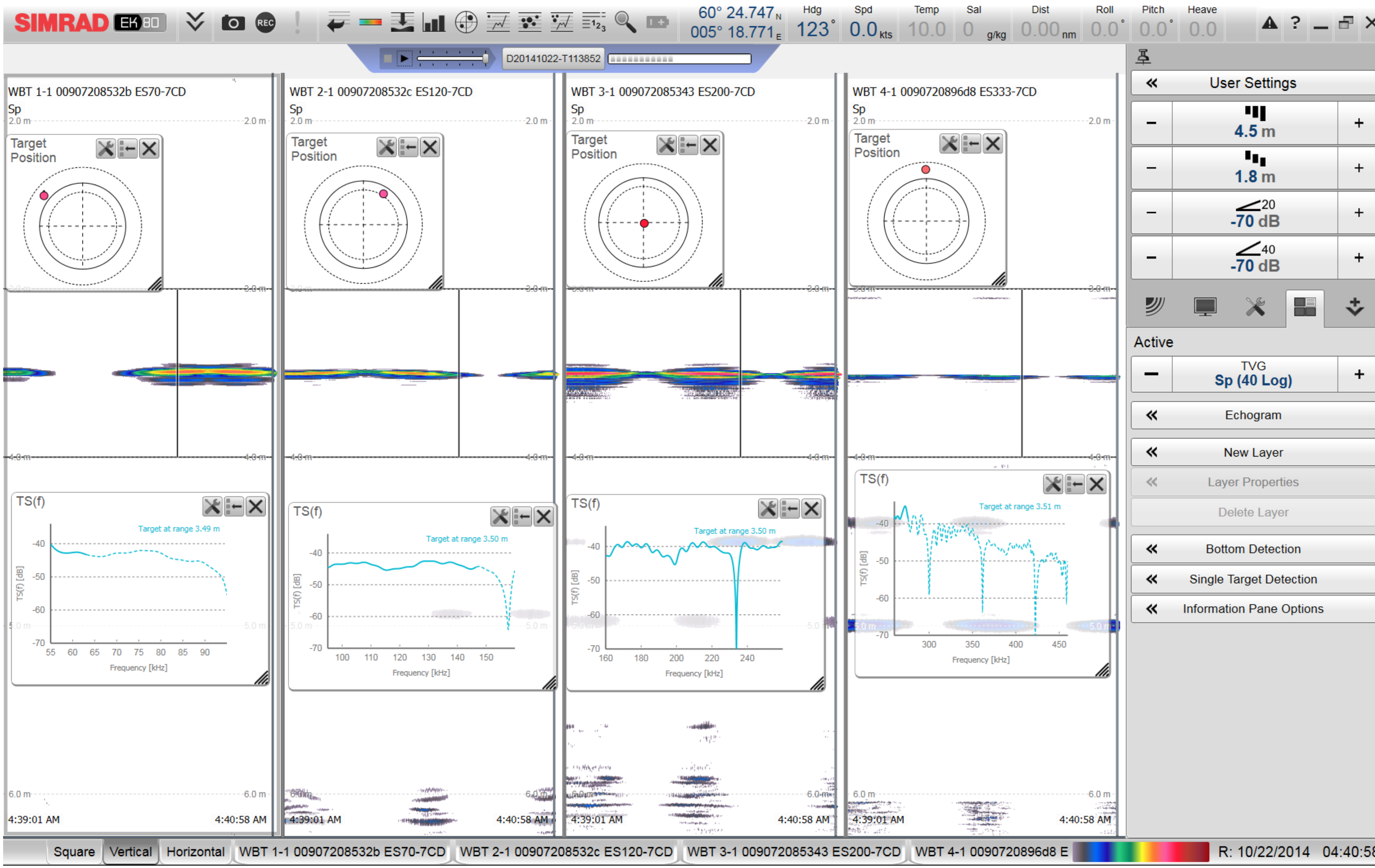


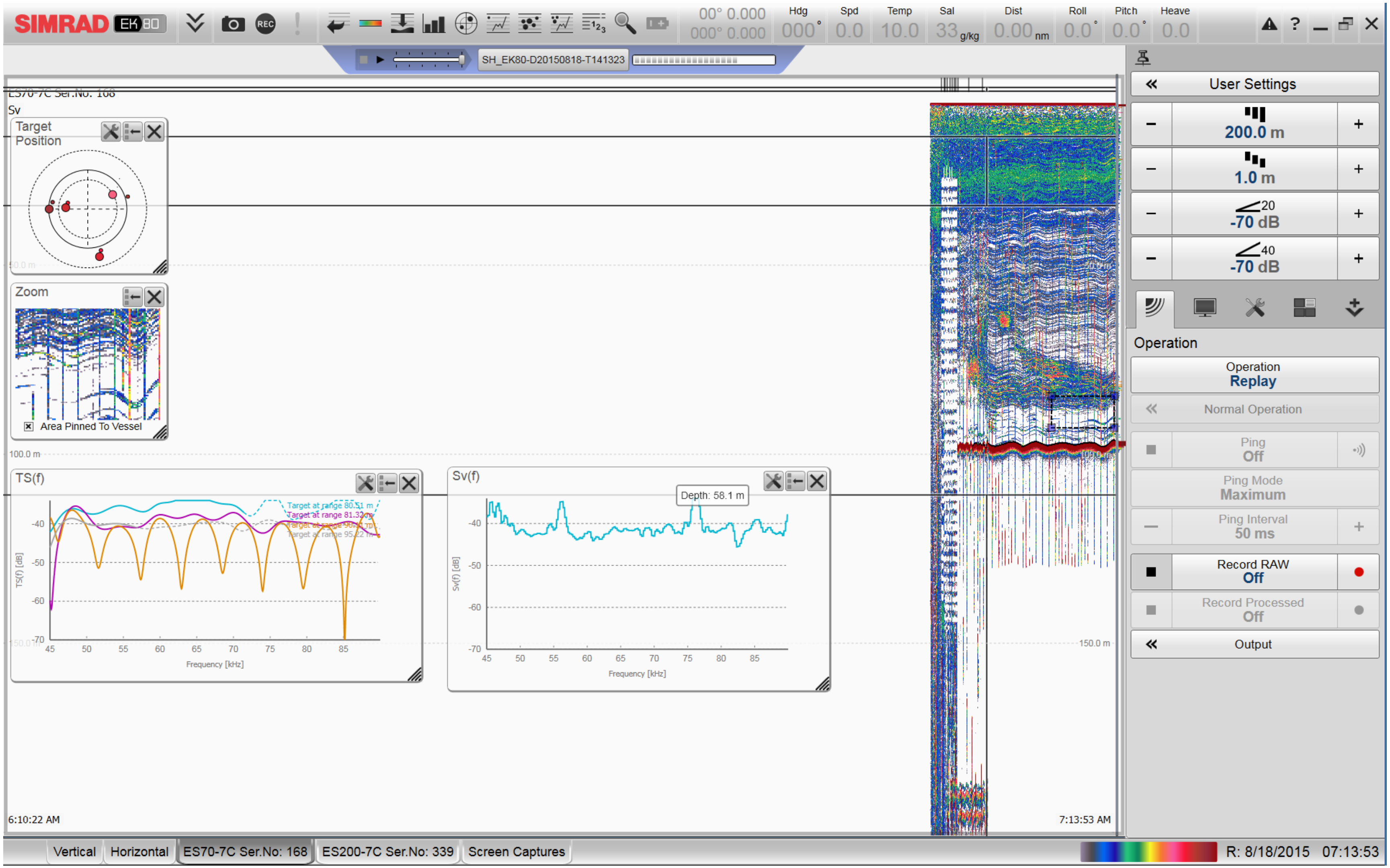
# Instrument GUI interface



# Instrument GUI interface (2013 calibration)



# Multiple targets (2015 hake survey)



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# Two Representative Systems

- EdgeTech (towed & vertically deployed applications)
- Simrad EK80

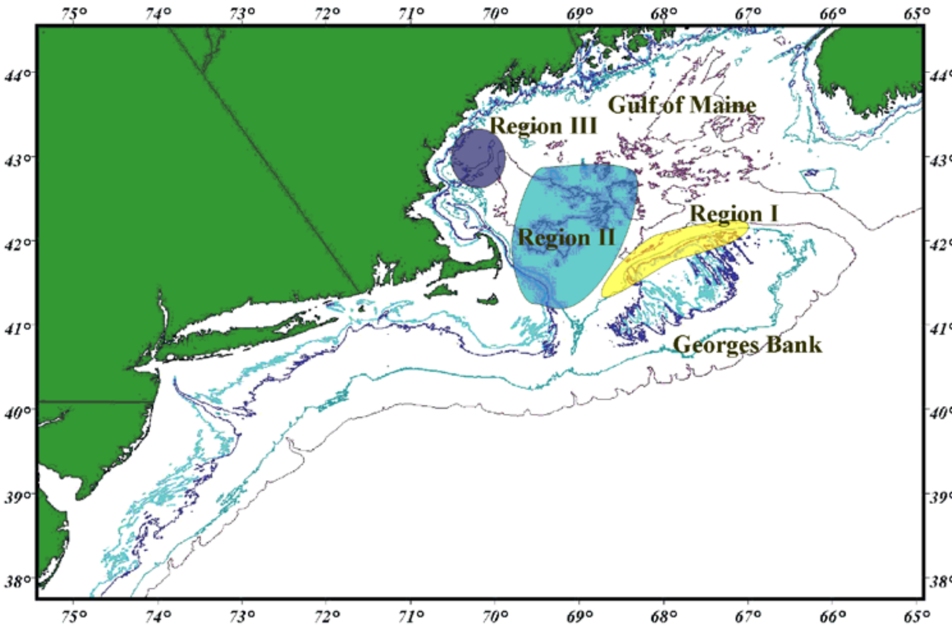
# Two Representative Systems

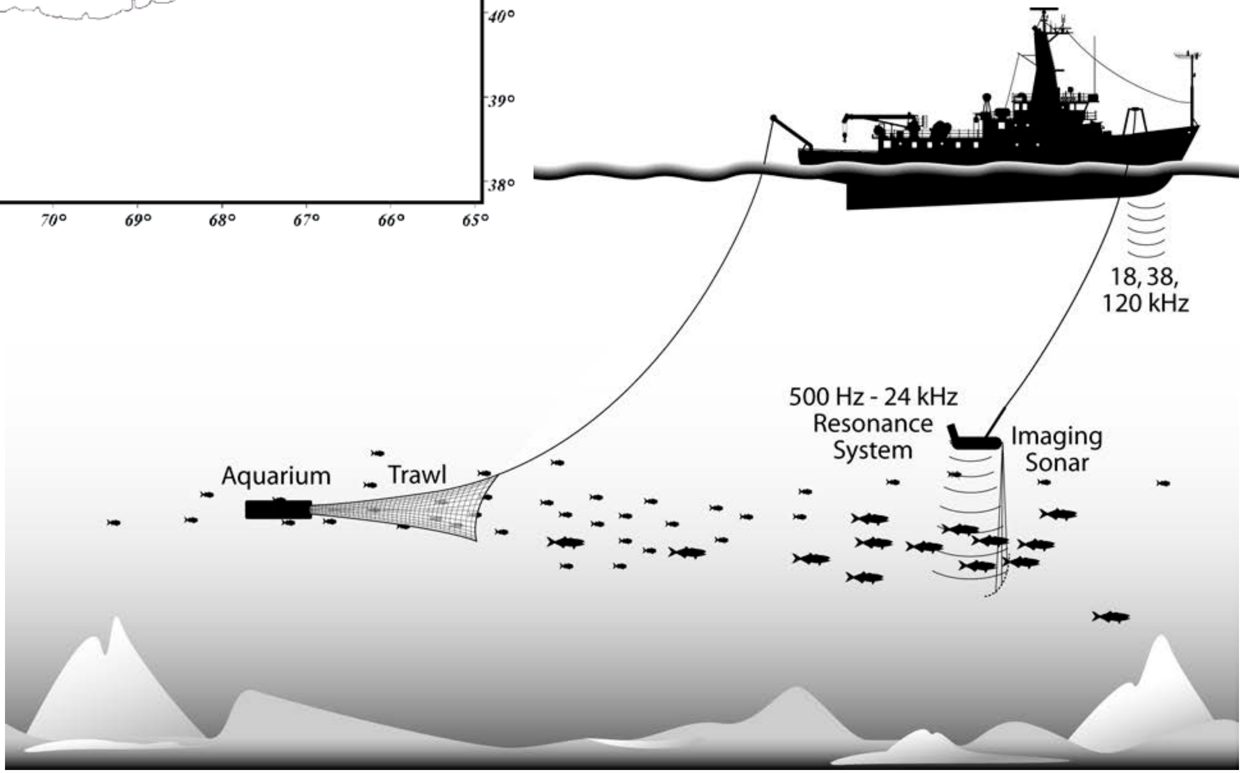
- EdgeTech (towed & vertically deployed applications)
- Simrad 80

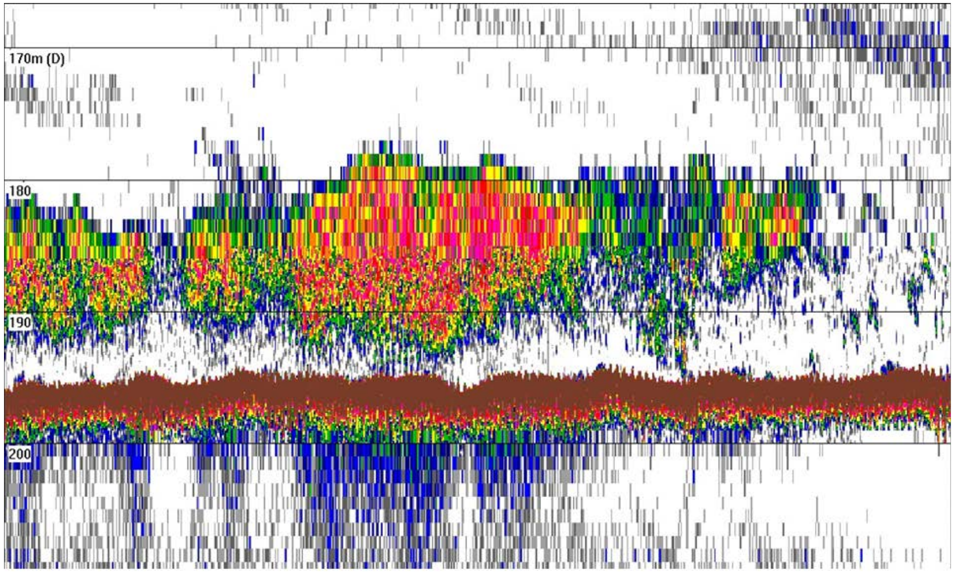
# Edgetech broadband system: 1-105 kHz

Winch for deployment (1,000 m cable)

# September, 2005 cruise (herring survey)

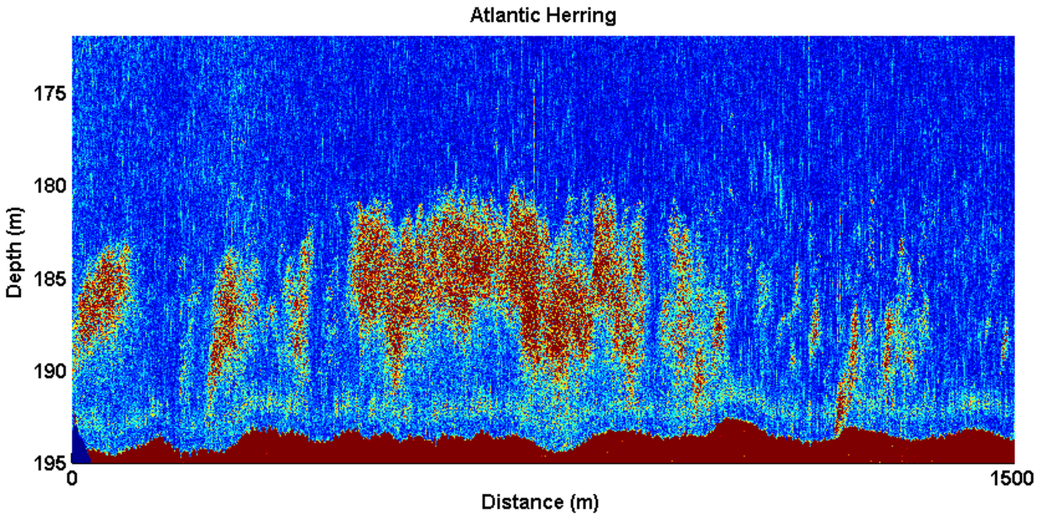





Traditional system

(120 kHz narrowband)

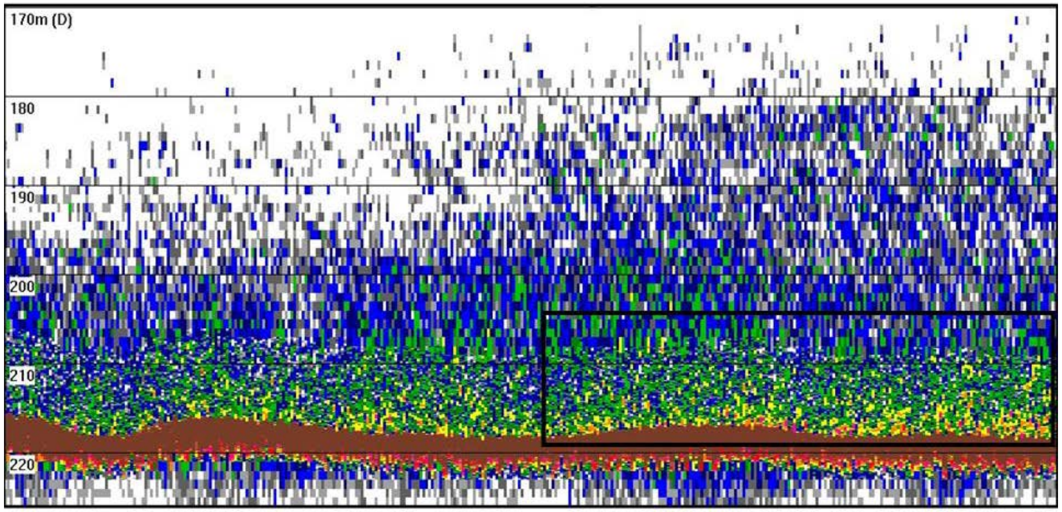



New system

(lower frequency, broadband)

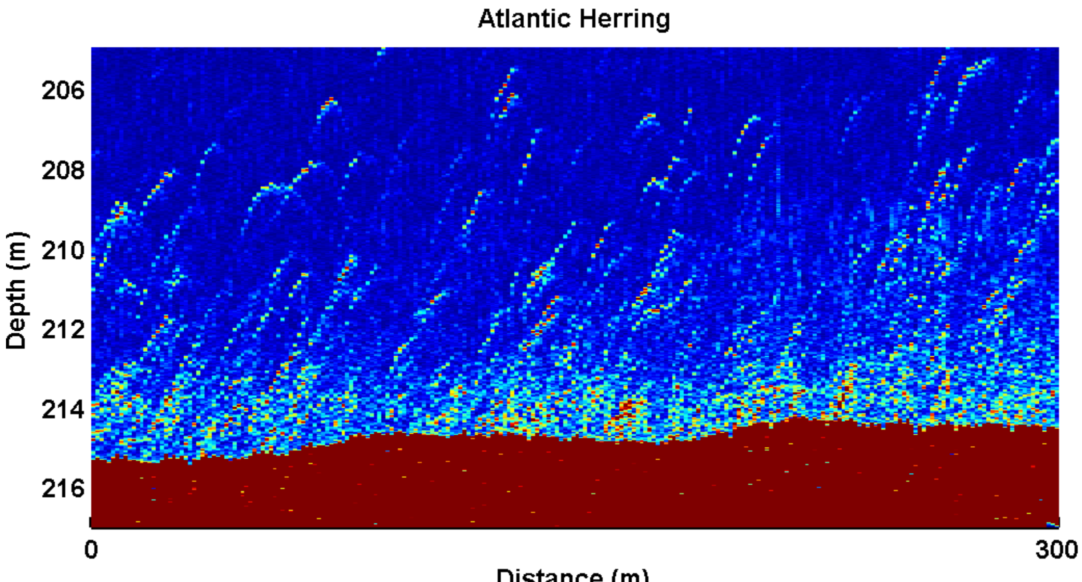
- Improved resolution: Broad bandwidth, pulse compression processing and flying low

- Reduced ambiguity: Lower frequency naturally “selects” only swimbladder-bearing fish




## Traditional system

(120 kHz narrowband)



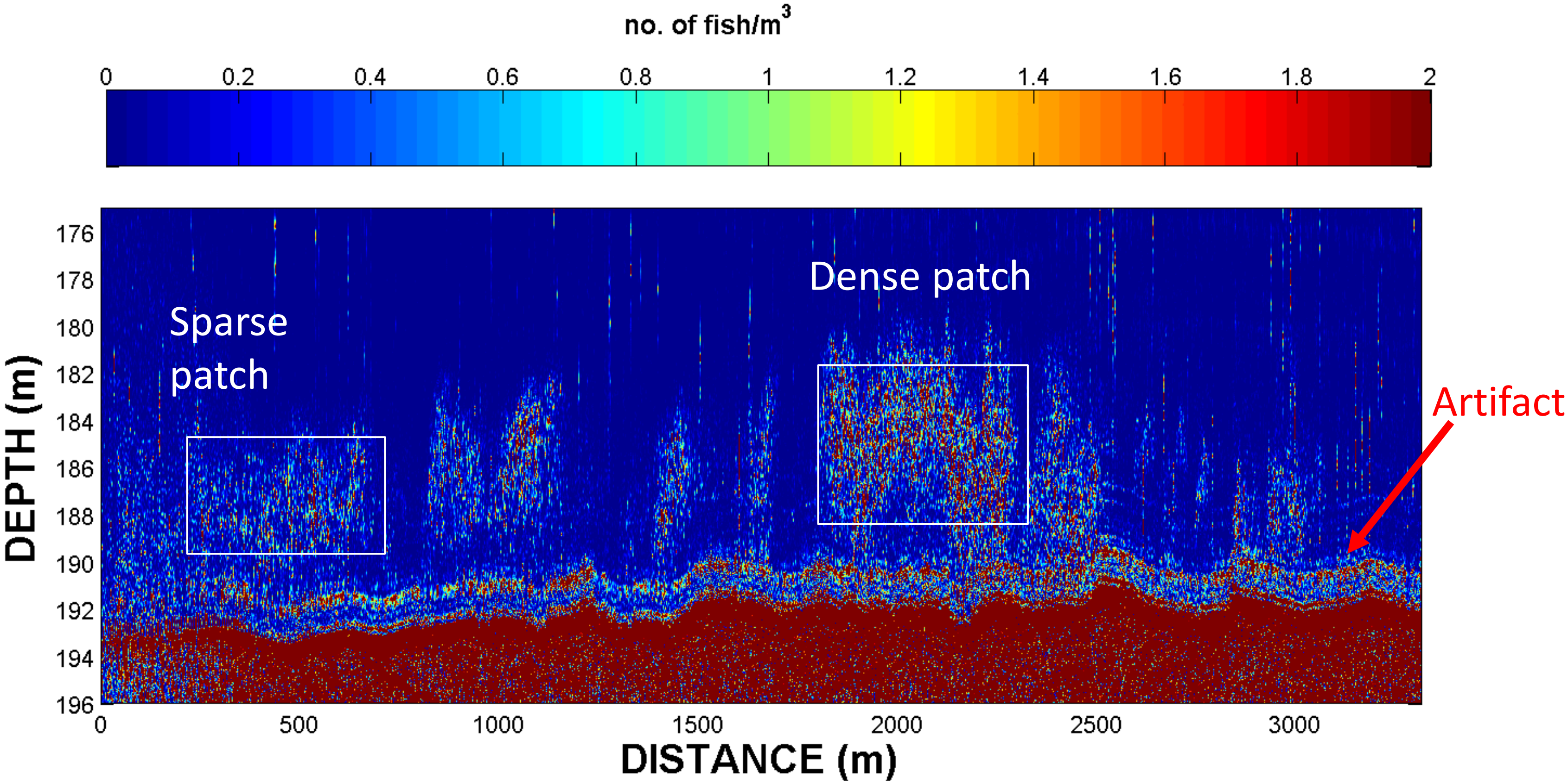

## New system

(lower frequency, broadband)

- Improved resolution: Broad bandwidth, pulse compression processing and flying low
- Reduced ambiguity: Lower frequency naturally "selects" only swimbladder-bearing fish

# Estimates of fish density

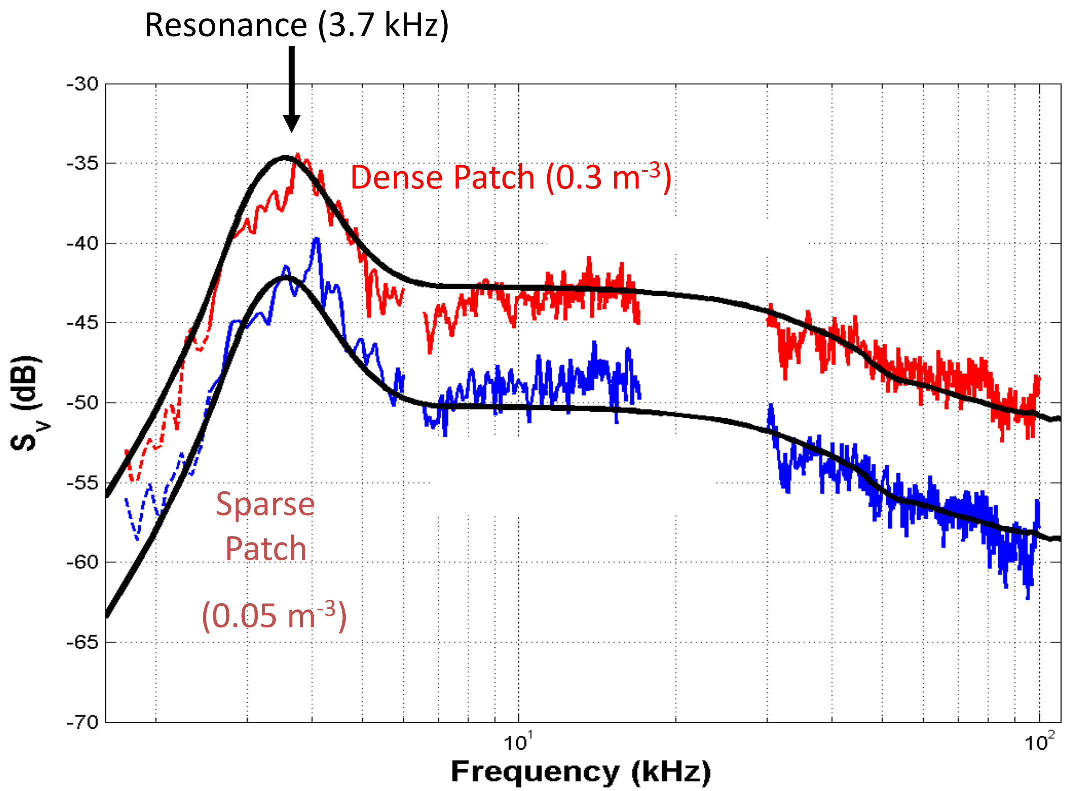
Using resonance classification at 2-6 kHz




- No ambiguities due to fish size or orientation distribution

# Resonance Classification – 1 (data)

(Atlantic Herring)

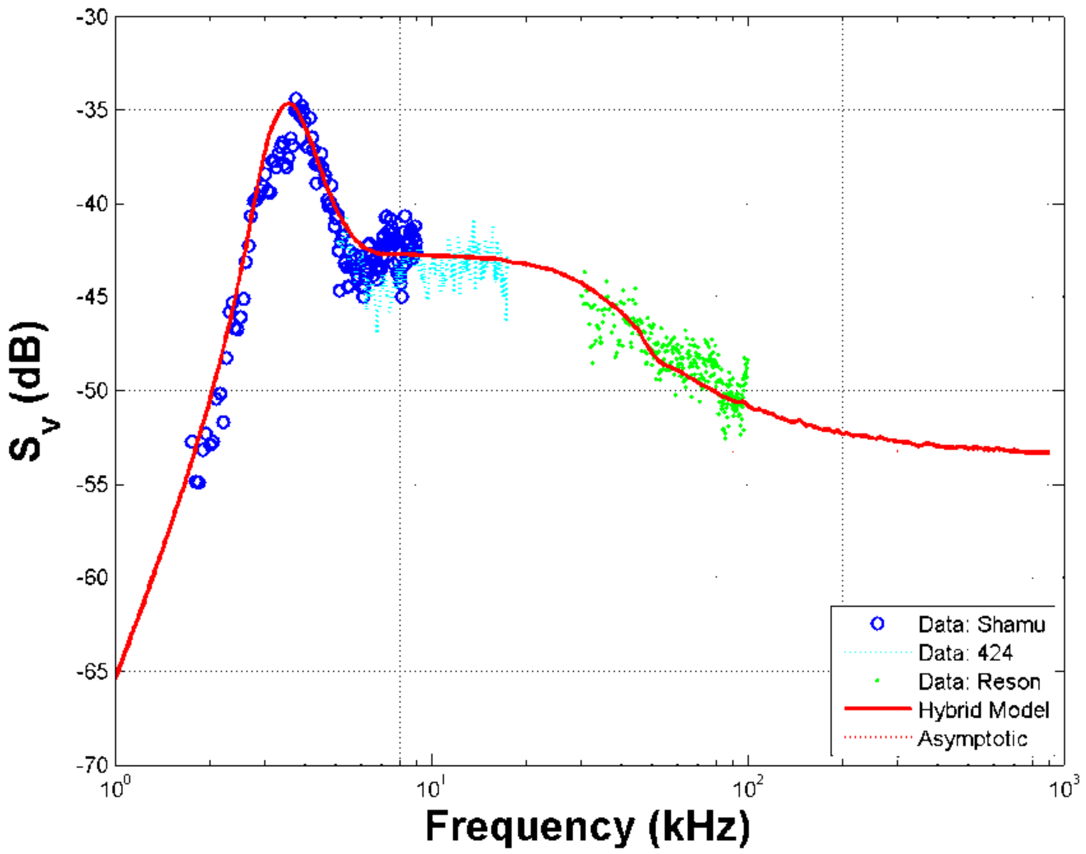



- Observations: Strong echo (upper) and weak echo (lower) have same resonance frequency
- Reduced ambiguities: Difference in echo strength is due to difference in density of fish, not size of fish or its orientation distribution

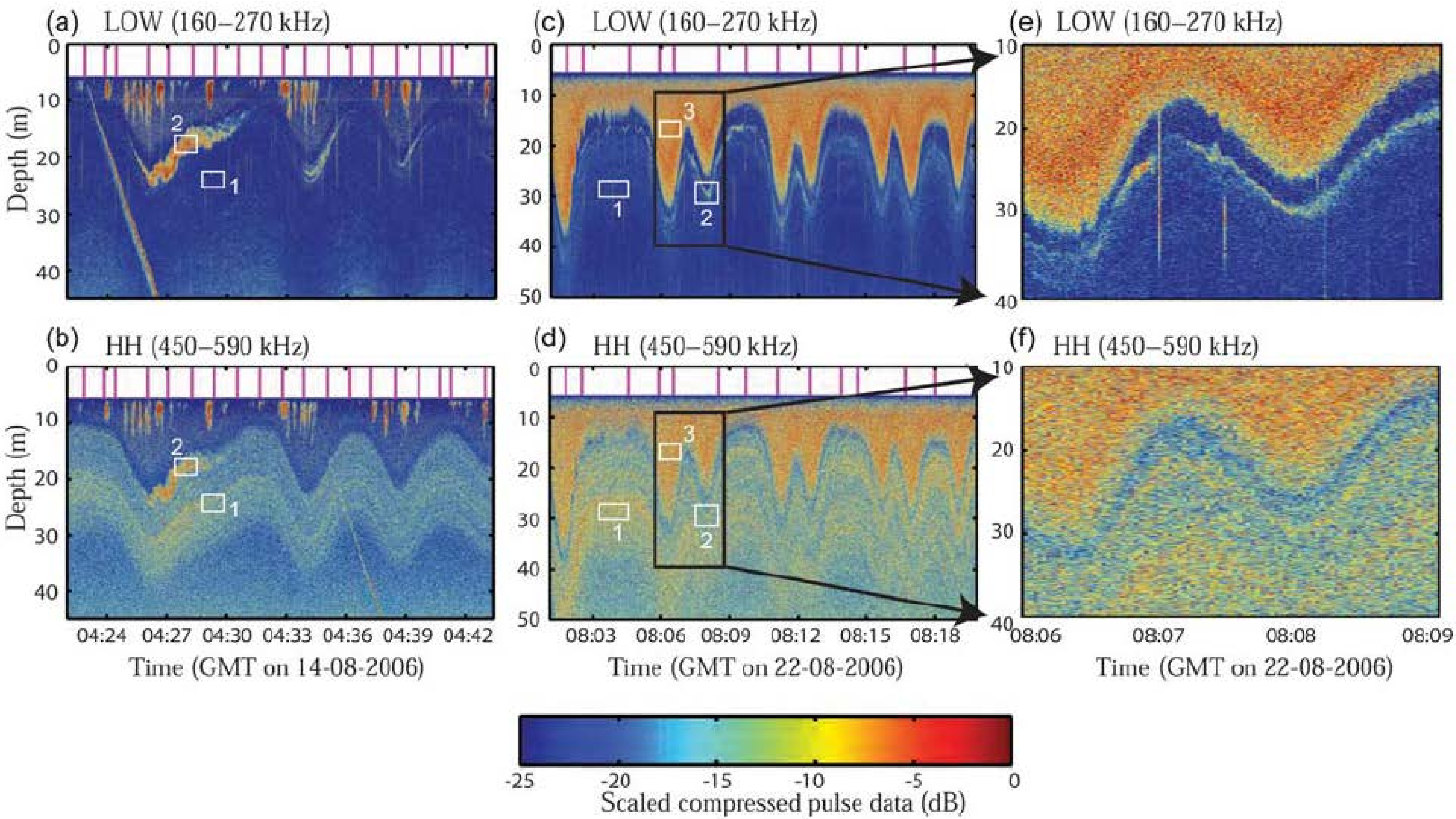
# Resonance Classification - 2

(Atlantic Herring)

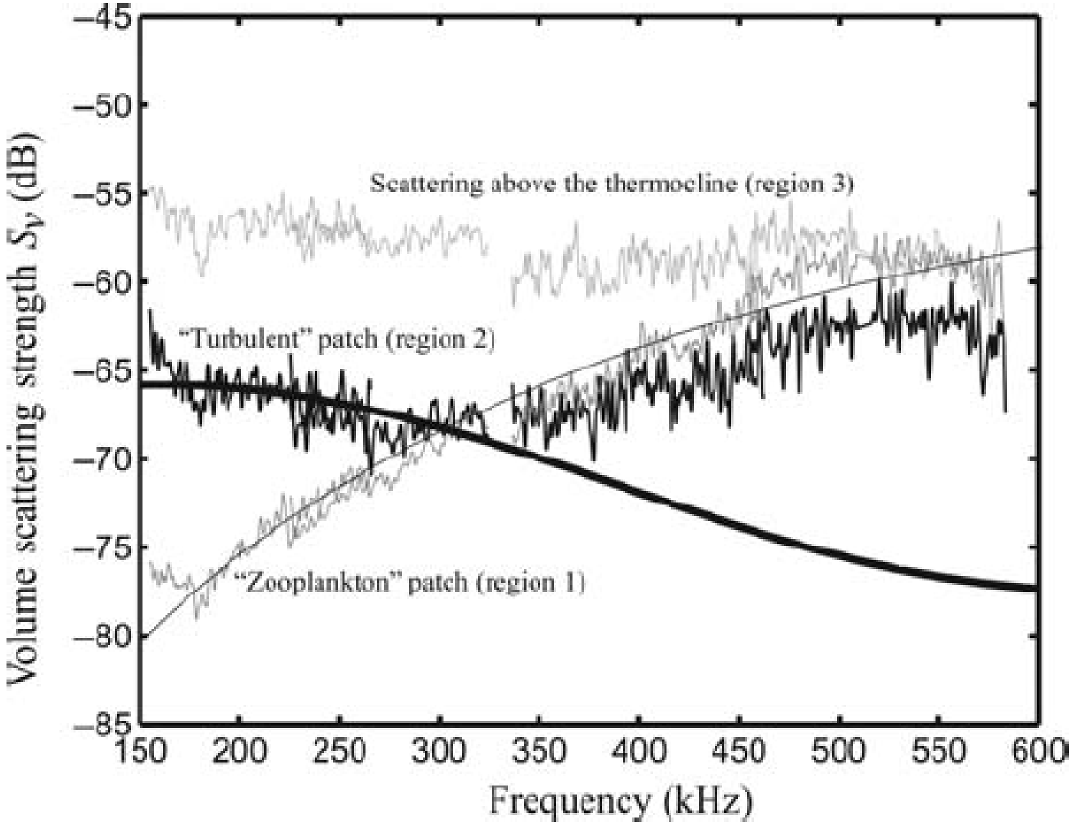
Model & Data comparison



# Internal wave (turbulent microstructure) & zooplankton scattering - 1



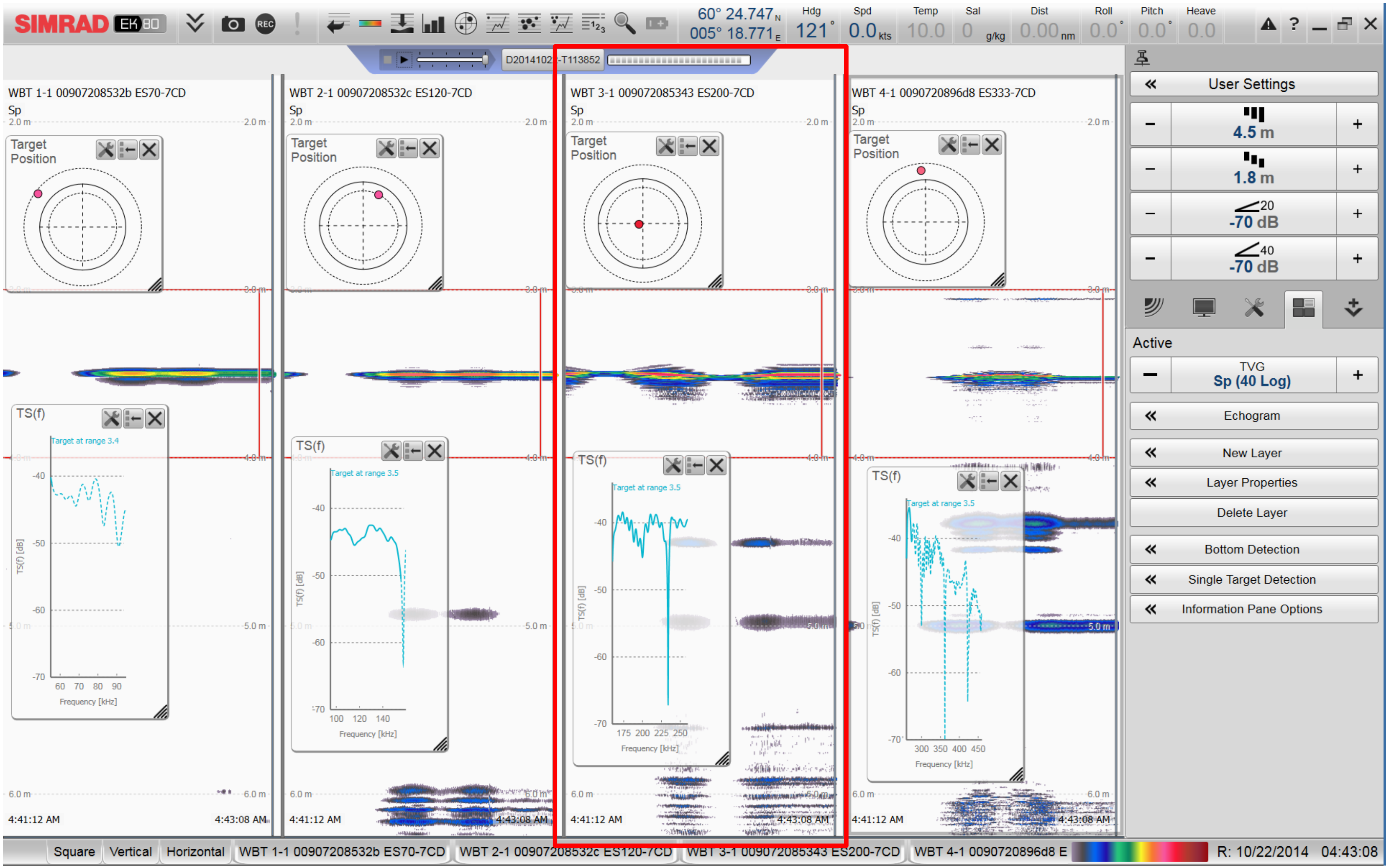
# Internal wave (turbulent microstructure) & zooplankton scattering - 2



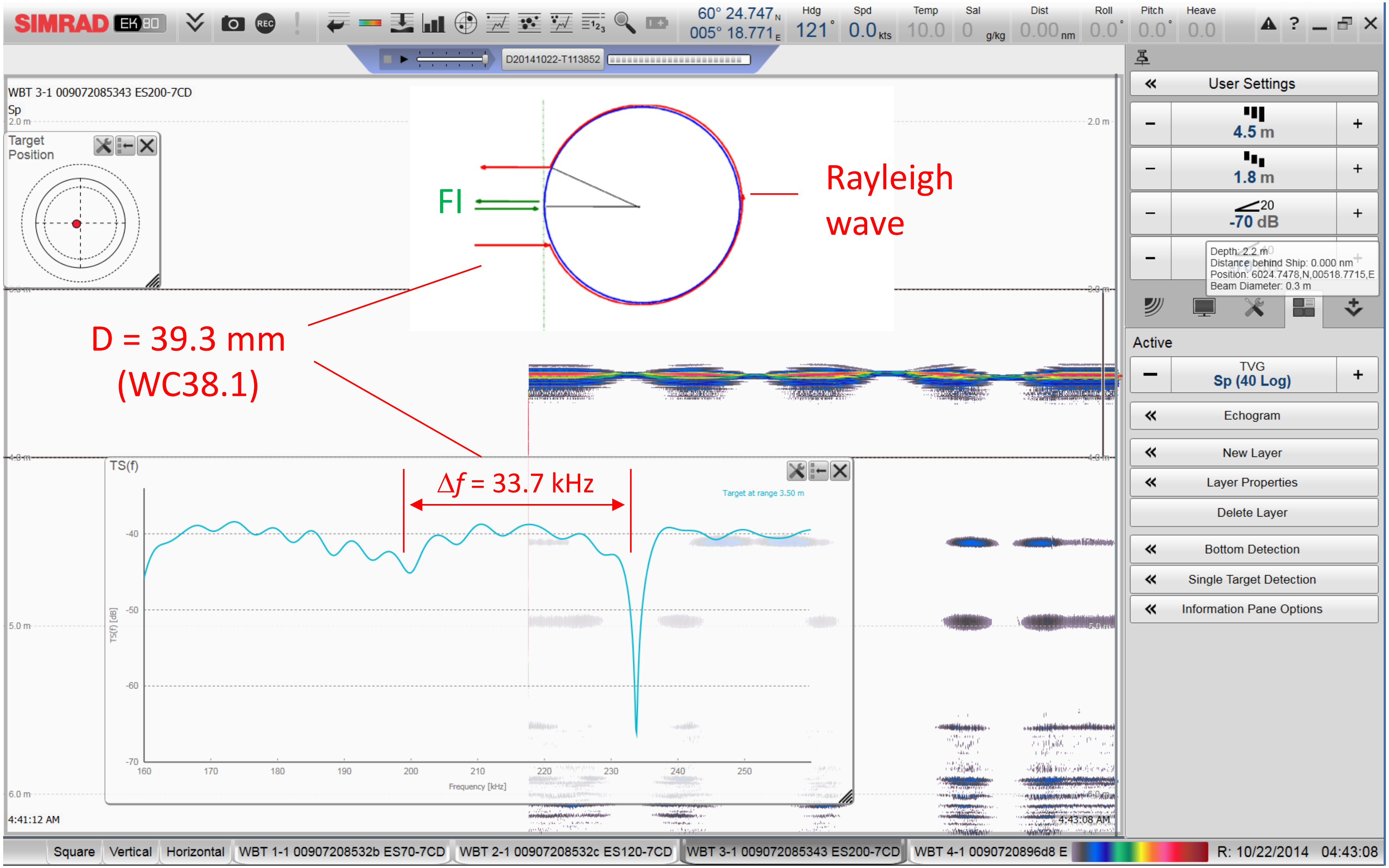
# Two Representative Systems

- EdgeTech (towed & vertically deployed applications)
- Simrad EK80

# Scattering by an elastic sphere



# Rayleigh Wave & target sizing

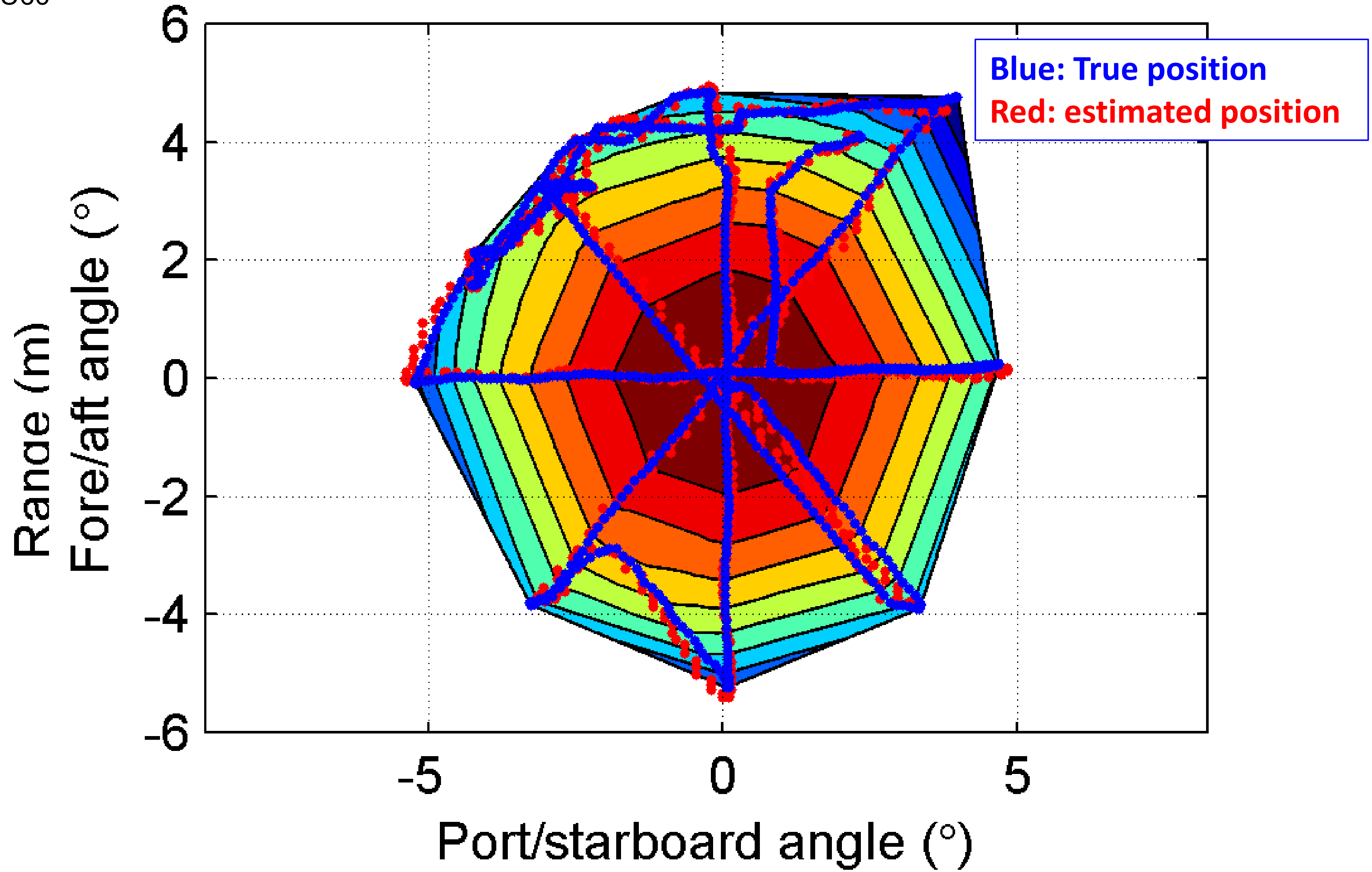


# Target Localization Experiments

- *G.O. Sars*, November 2010
- IMR TSprobe
- Response from calibration spheres
  - WC20, 22, 75
  - CU60
- Systems at 70, 120, 200, 333 kHz
- 50% shaded chirp pulse

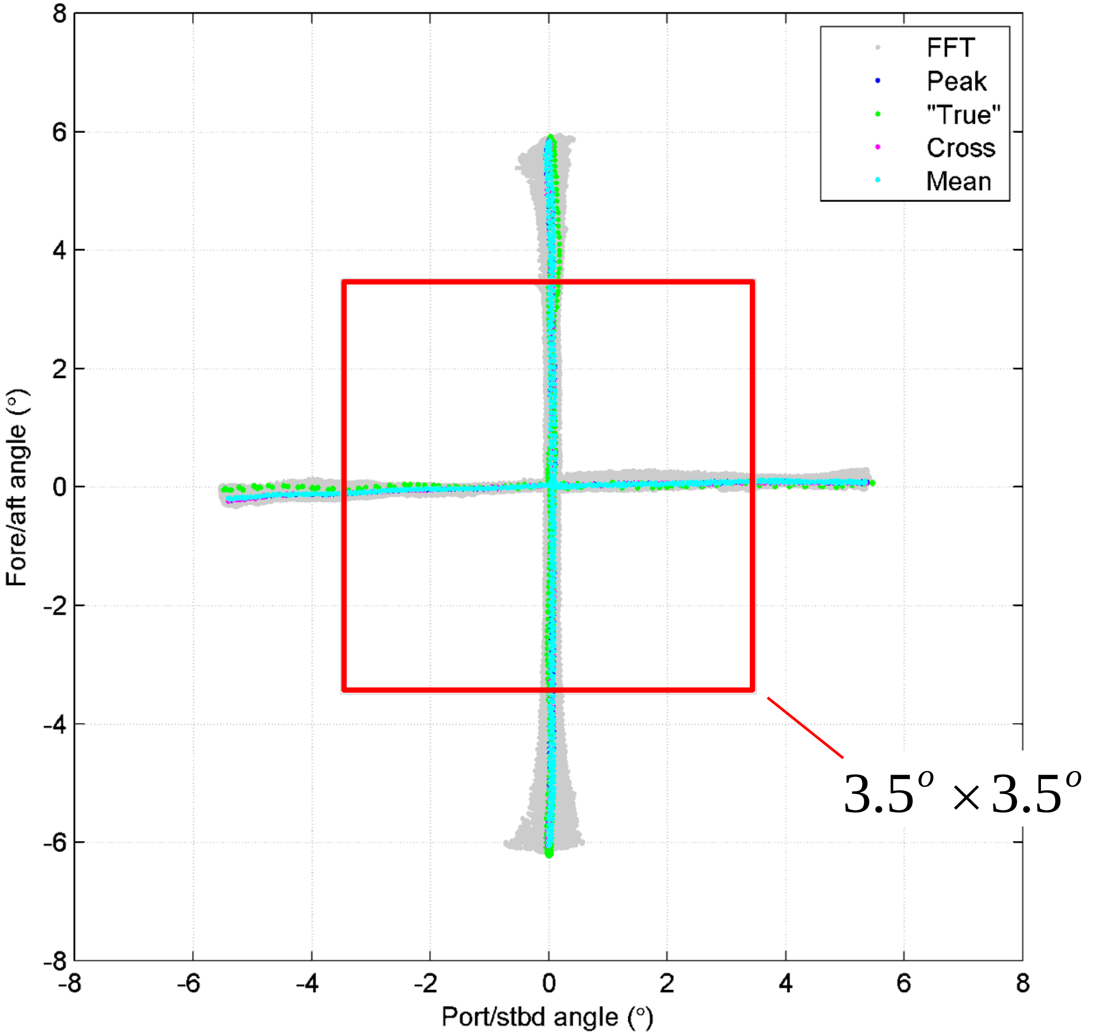
# TS Probe with extended arms

CU60



Blue: True position
Red: estimated position
6
4
2
0
-2
-4
-6
Range (m)
Fore/aft angle (°)
-5
0
5
Port/starboard angle (°)

CU60, 70 kHz

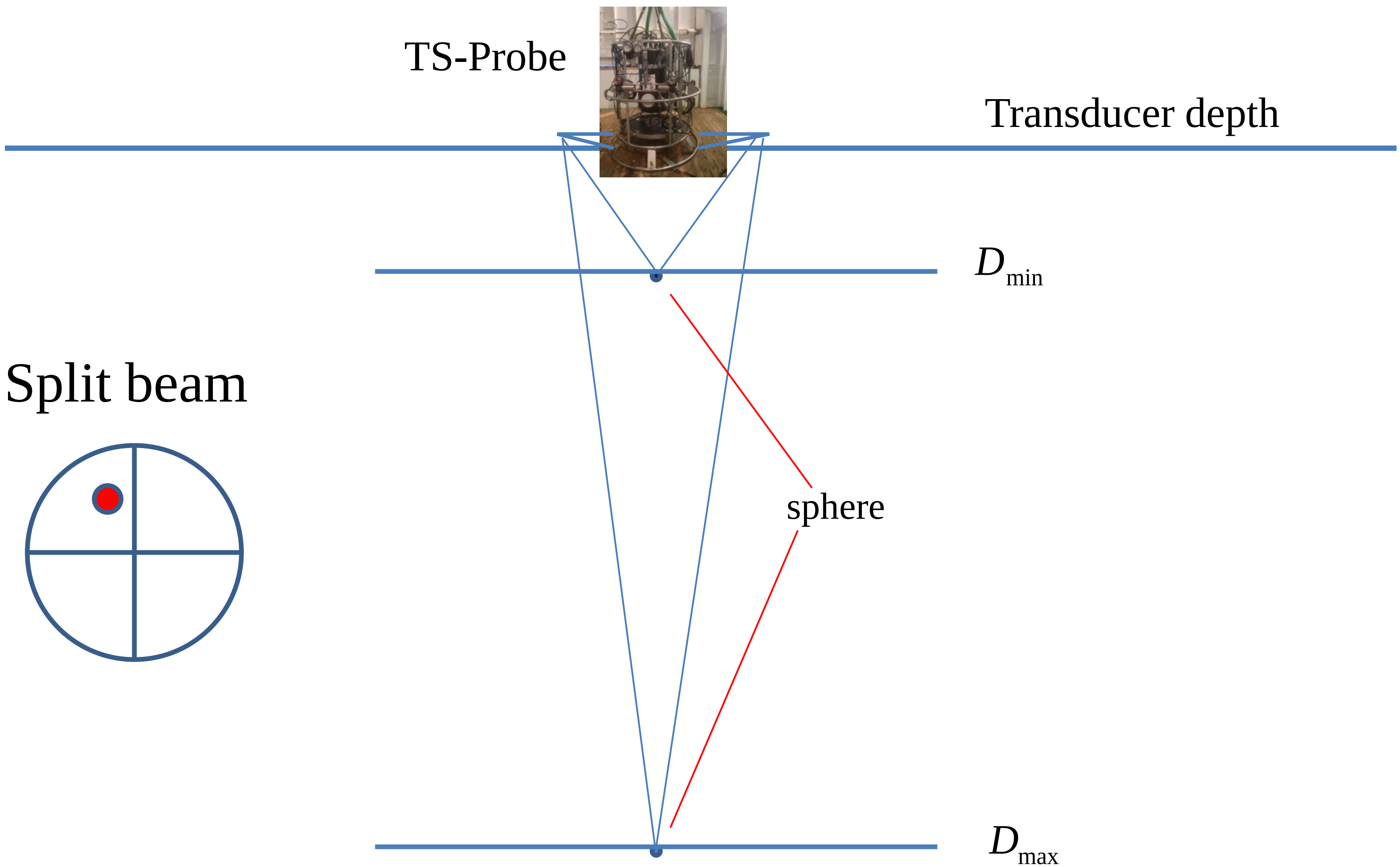

FFT
Peak
"True"
Cross
Mean
Fore/aft angle (°)
Port/stbd angle (°)
8
6
4
2
0
-2
-4
-6
-8
$3.5^o \times 3.5^o$

# Seawater Absorption Coefficient Experiment

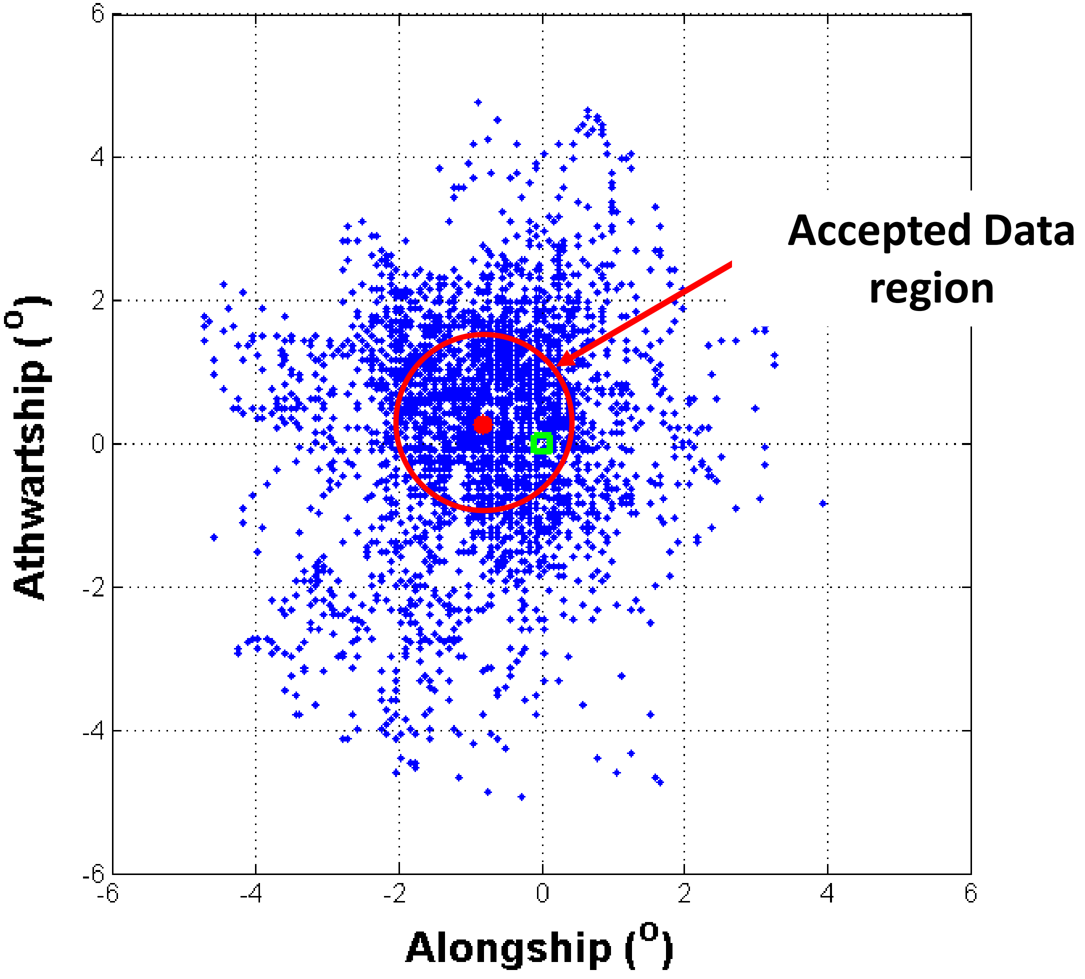
R/V G. O. SARS

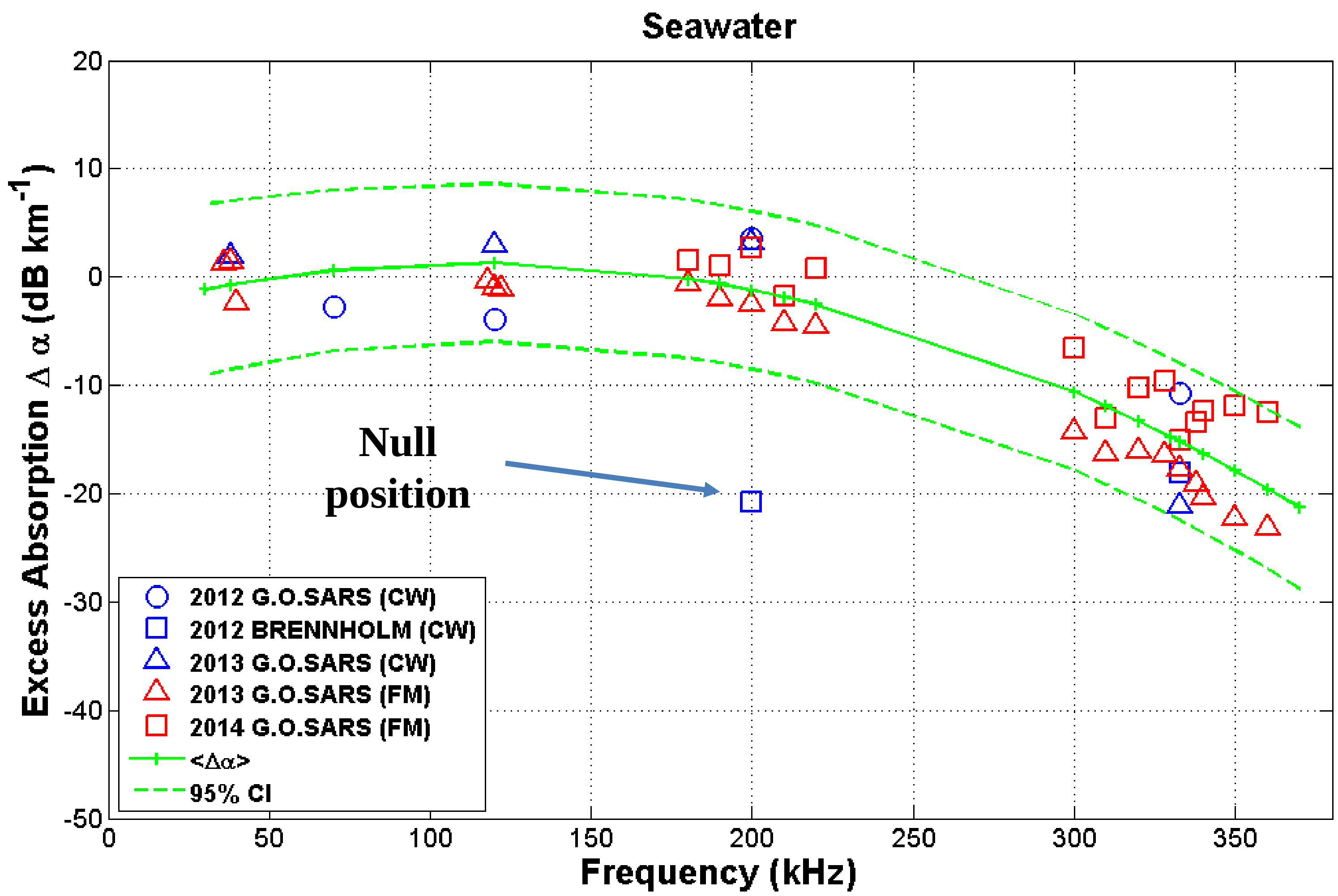
2012-2014, Norwegian Fjords

# Experiment Configuration



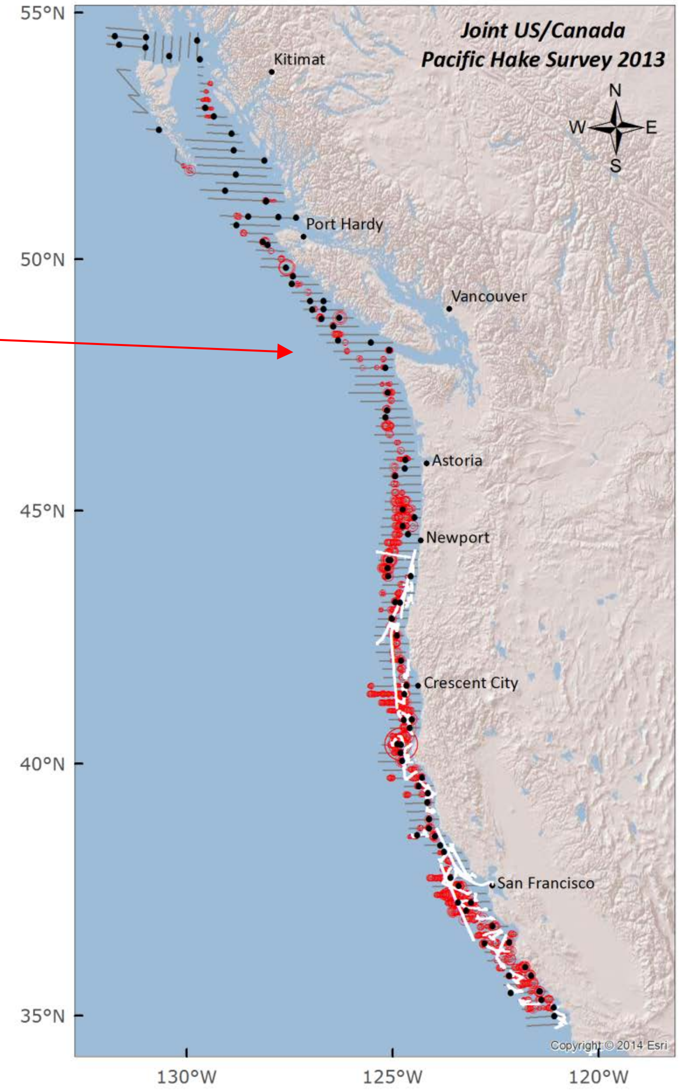
# Determination of the sphere location



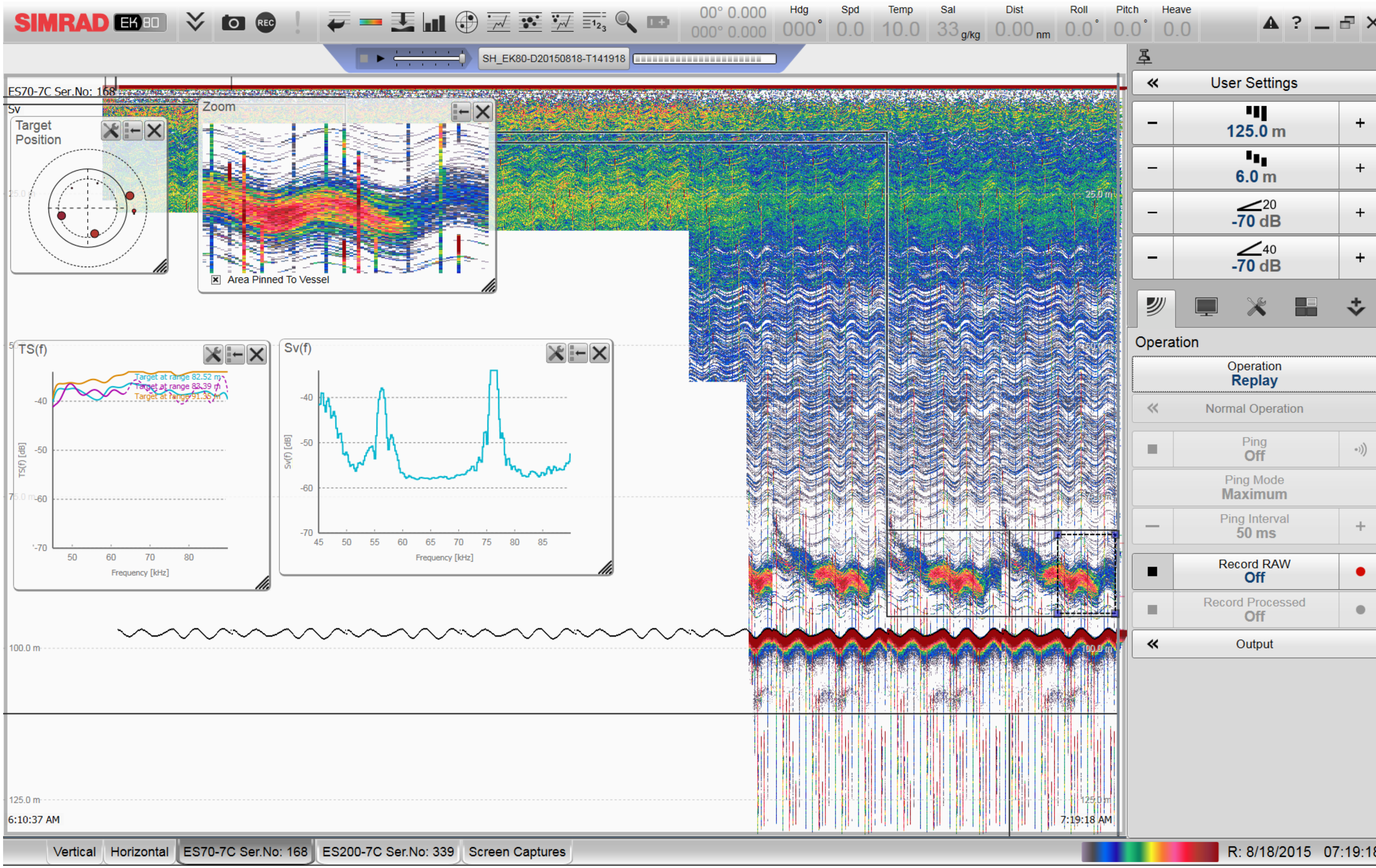

Seawater
Excess Absorption Δ α (dB km⁻¹)
Frequency (kHz)
20
10
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350
Null position
2012 G.O.SARS (CW)
2012 BRENNHOLM (CW)
2013 G.O.SARS (CW)
2013 G.O.SARS (FM)
2014 G.O.SARS (FM)
<Δα>
95% CI

# Pacific hake survey (Sake2015)

Re-run transect 55 with EK80



# EK80 Echogram



# Outlines

- Introduction
- Theoretical Background
- Broadband/wideband Systems
- Application
- Summary

# Advantages of Broadband/Wideband Echo Sounder Systems

- Higher SNR
- Higher temporal resolution
  - Target characterization (individual & aggregation)
- Continuous frequency response
  - Target classification

# Calibrations

- TS (resolved targets)
  - Frequency dependent gain
- Sv (un-resolved targets)
  - Frequency dependent 2-way beamangle
  - FFT window → effective time duration

Thank You!