Observations and modeling of angular compression and spatial coherence in sea surface forward scattering

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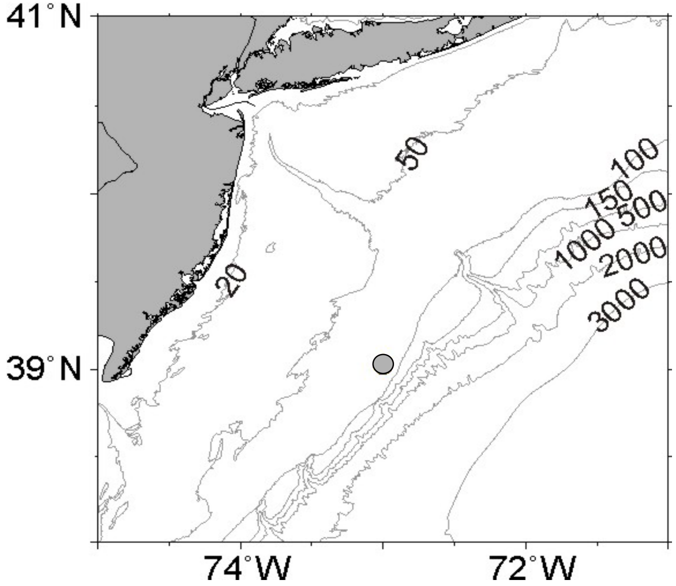
Spatial coherence in forward scattering from single (time resolved) interaction with sea surface from *Shallow Water 06*

Environment: Wind speed ~ 6 m/s, Waveheight ~ 0.15 m, stationary > 6 h

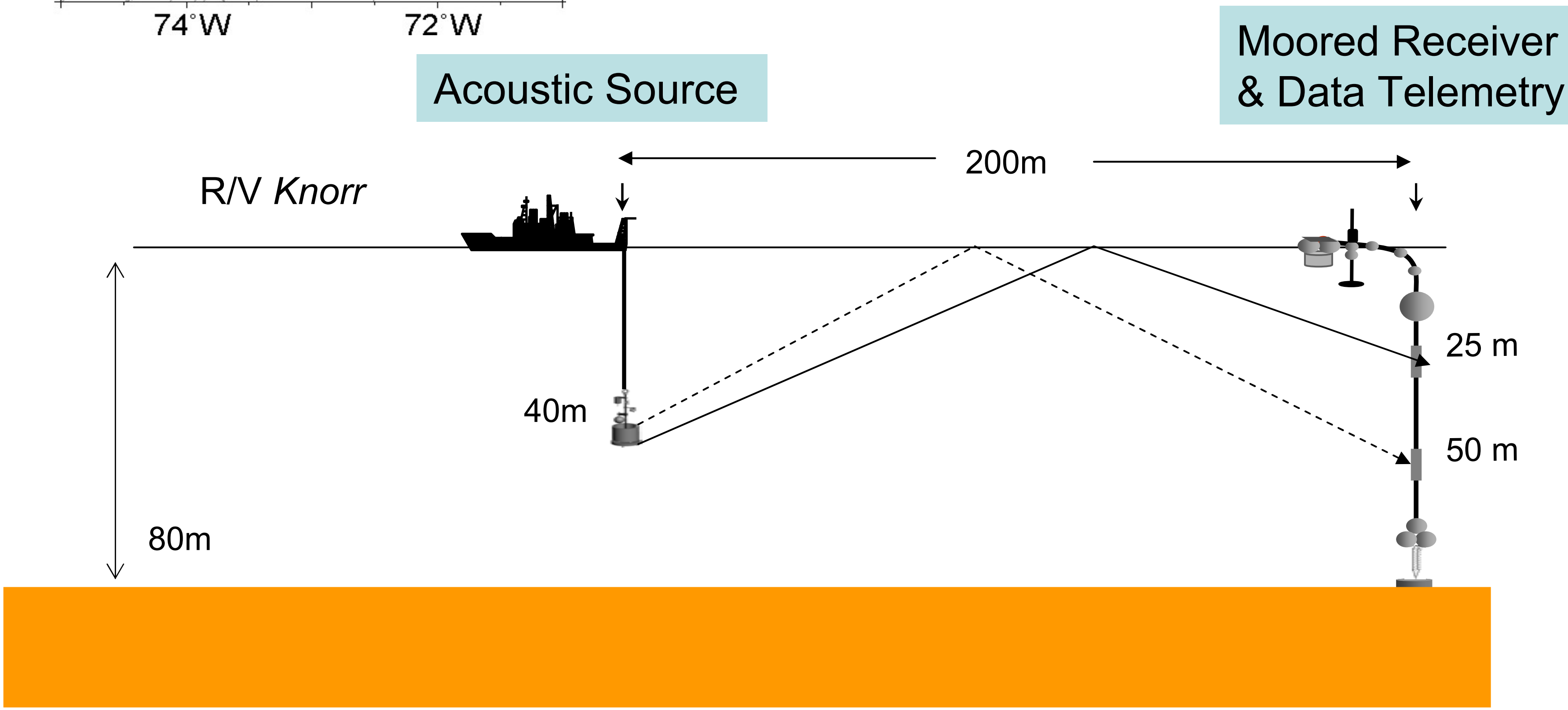
Comparative influence of sea surface C(Z) [thermocline]

Research sponsored by U.S. Office of Naval Research



Experimental site: off the New Jersey Continental Shelf, Water Depth 80 m

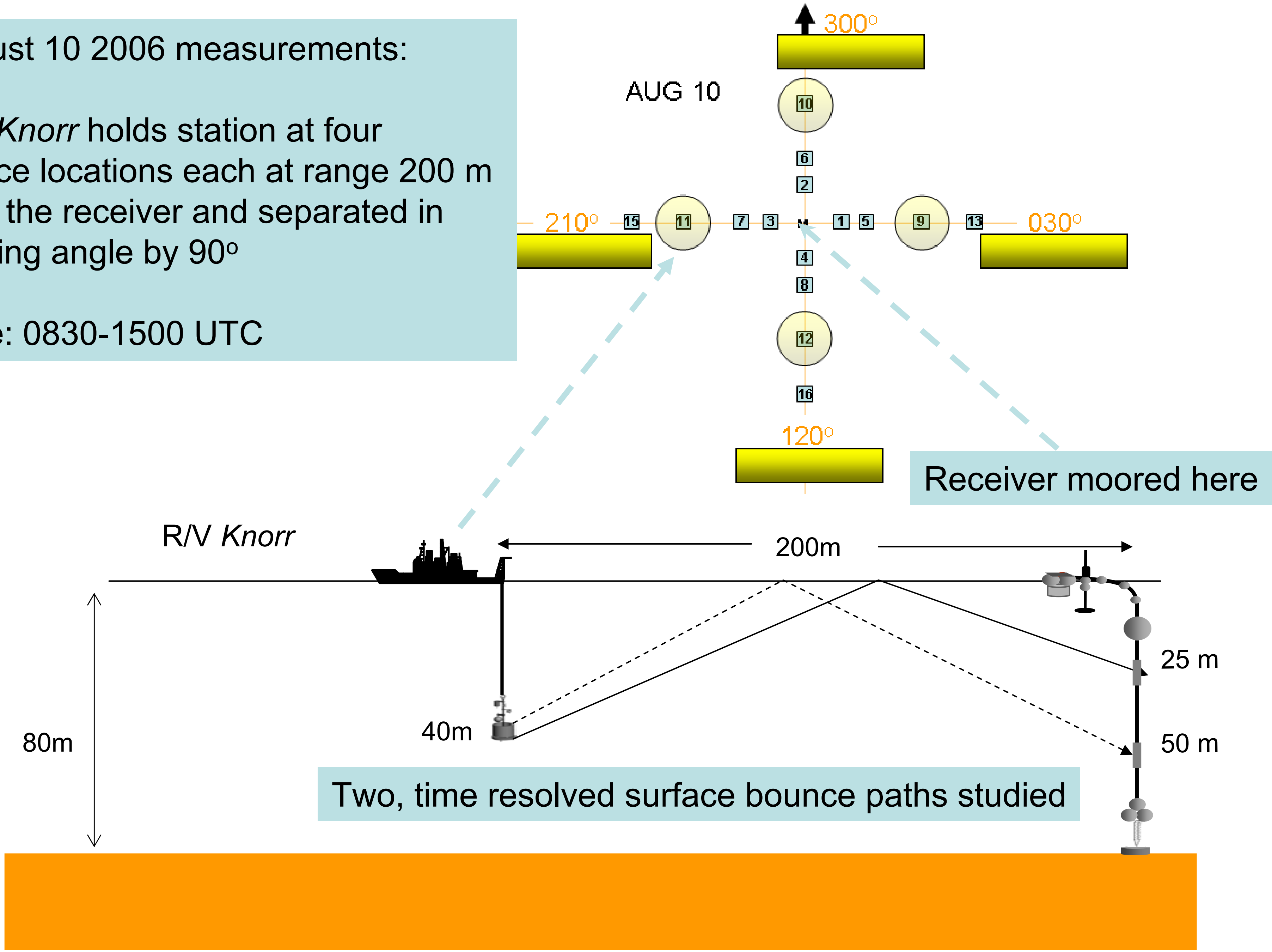
Shallow Water 06 (SW06) August 2006

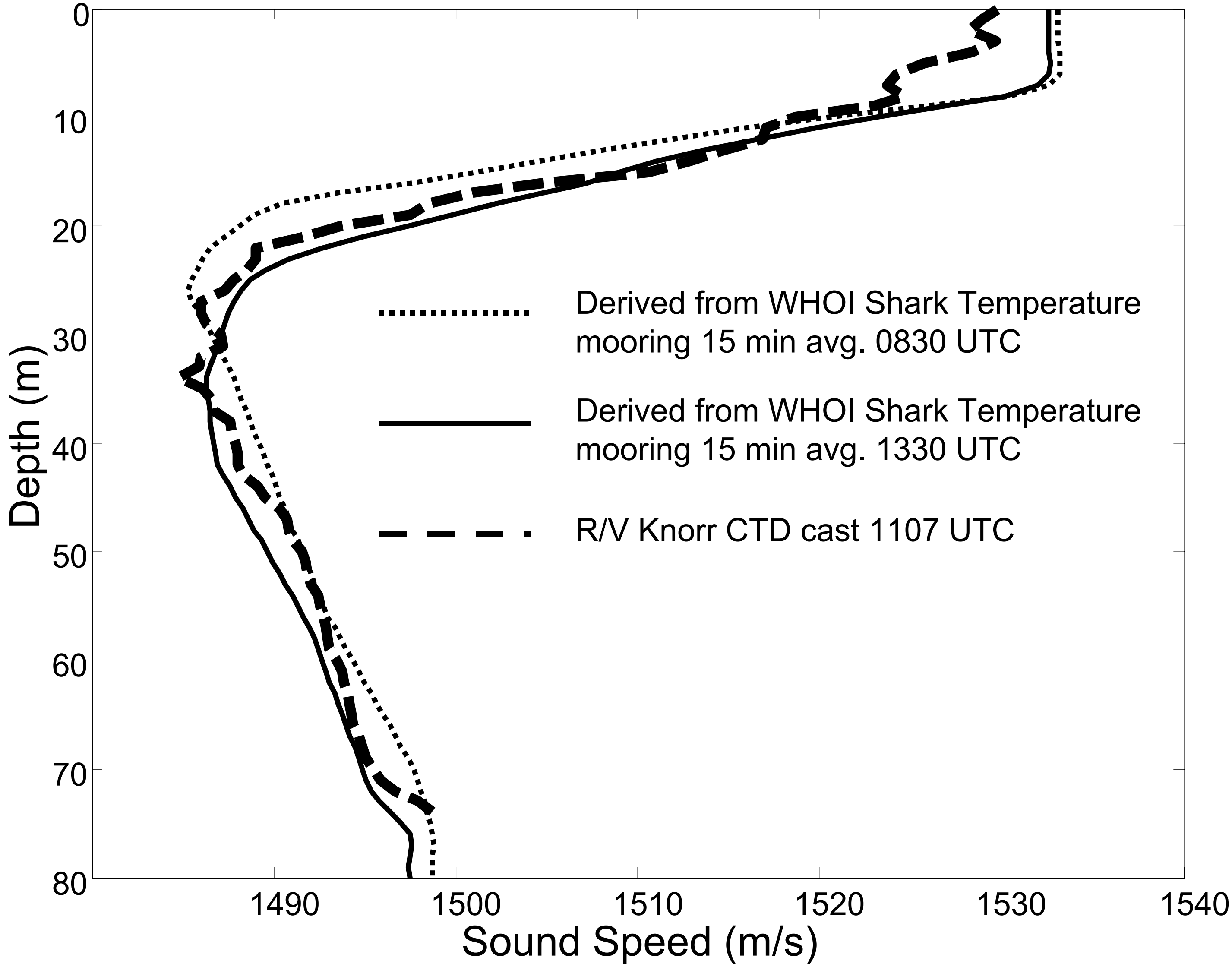


August 10 2006 measurements:

R/V *Knorr* holds station at four source locations each at range 200 m from the receiver and separated in bearing angle by 90º

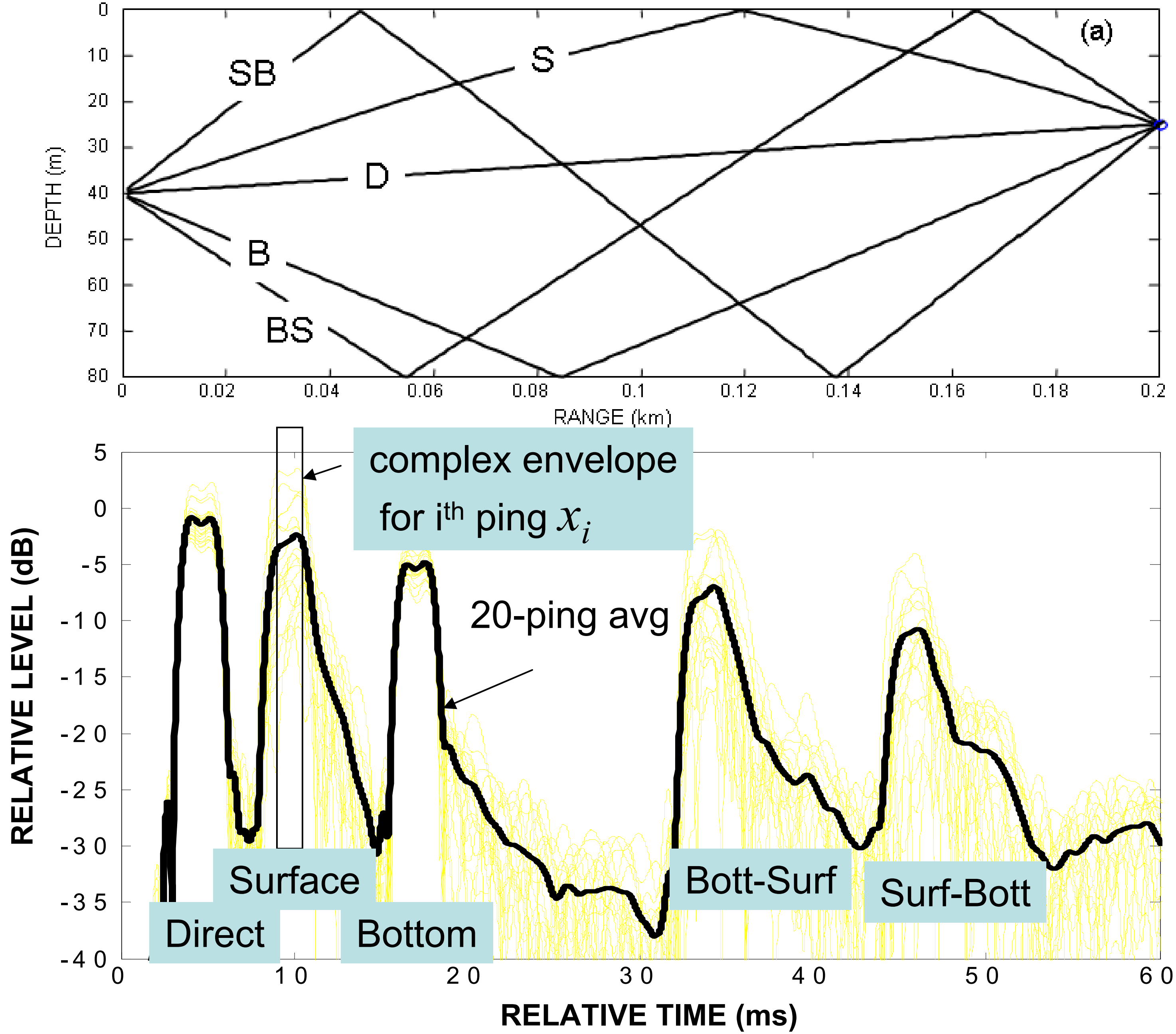
Time: 0830-1500 UTC

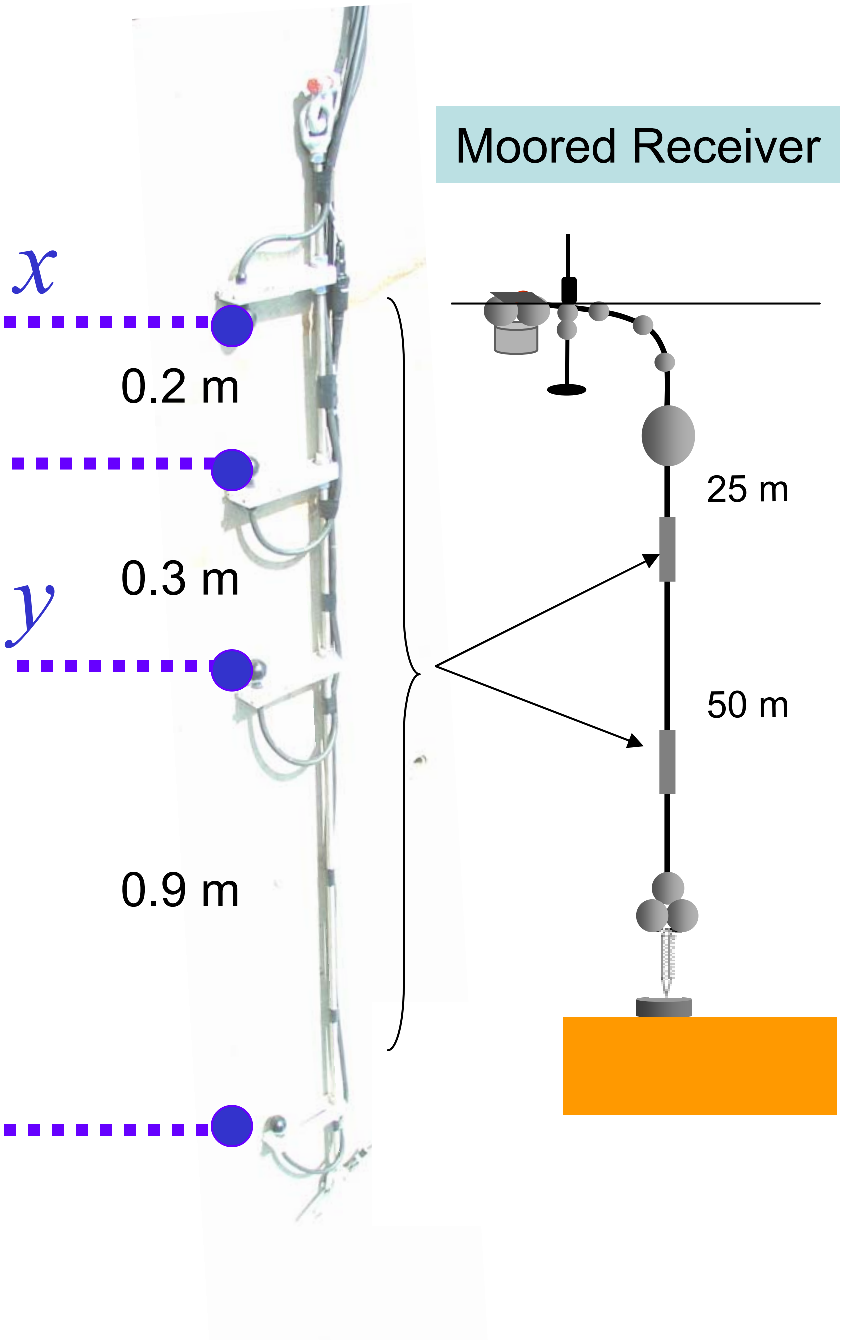




0
10
20
30
40
50
60
70
80
Depth (m)
1490
1500
1510
1520
1530
1540
Sound Speed (m/s)
Derived from WHOI Shark Temperature mooring 15 min avg. 0830 UTC
Derived from WHOI Shark Temperature mooring 15 min avg. 1330 UTC
R/V Knorr CTD cast 1107 UTC

upper receiver eigenrays and corresponding arrival structure



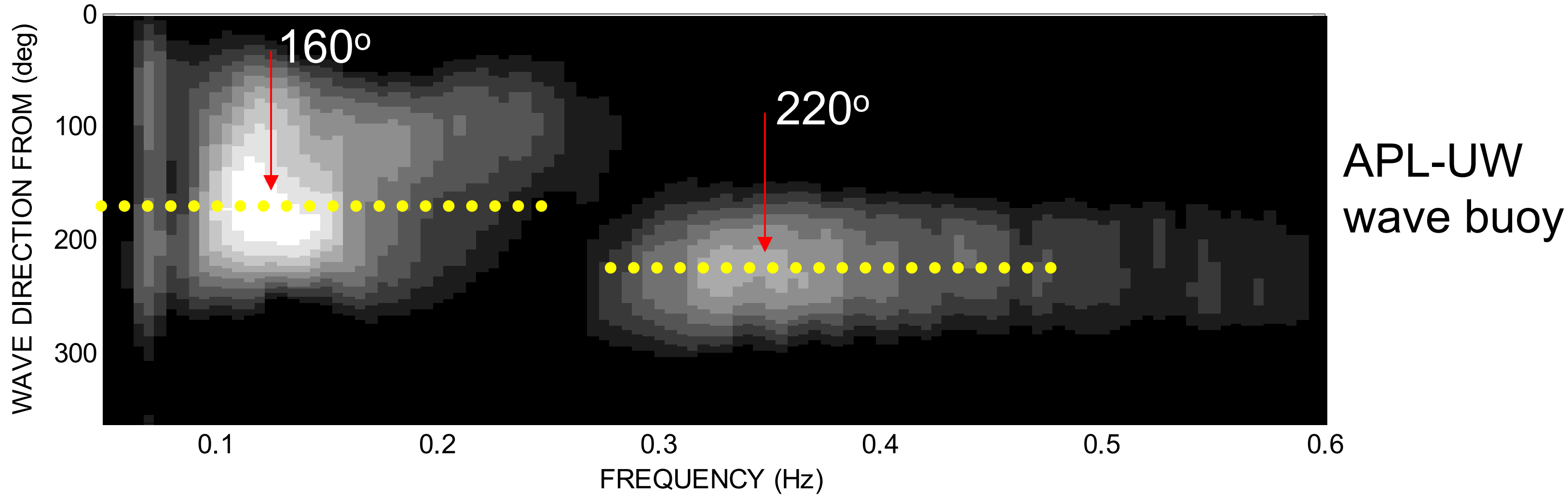


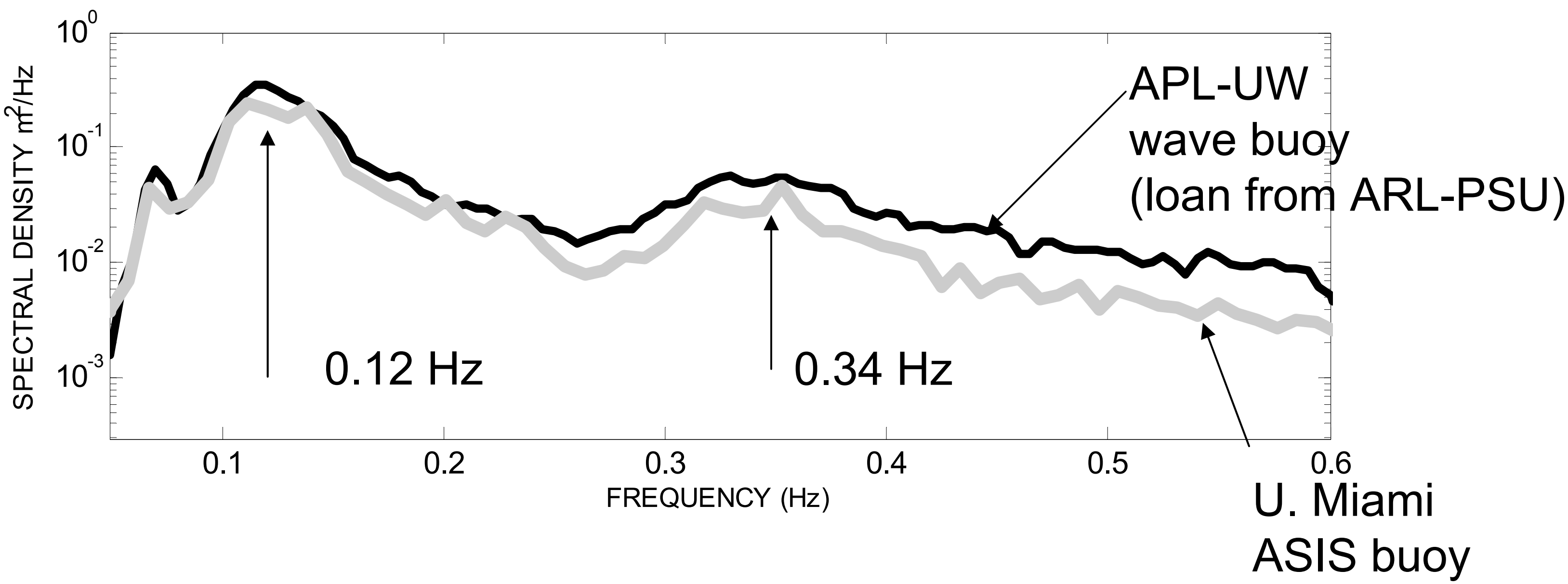
Spatial coherence between (d) vertically-separated channels based on 20 ping avg

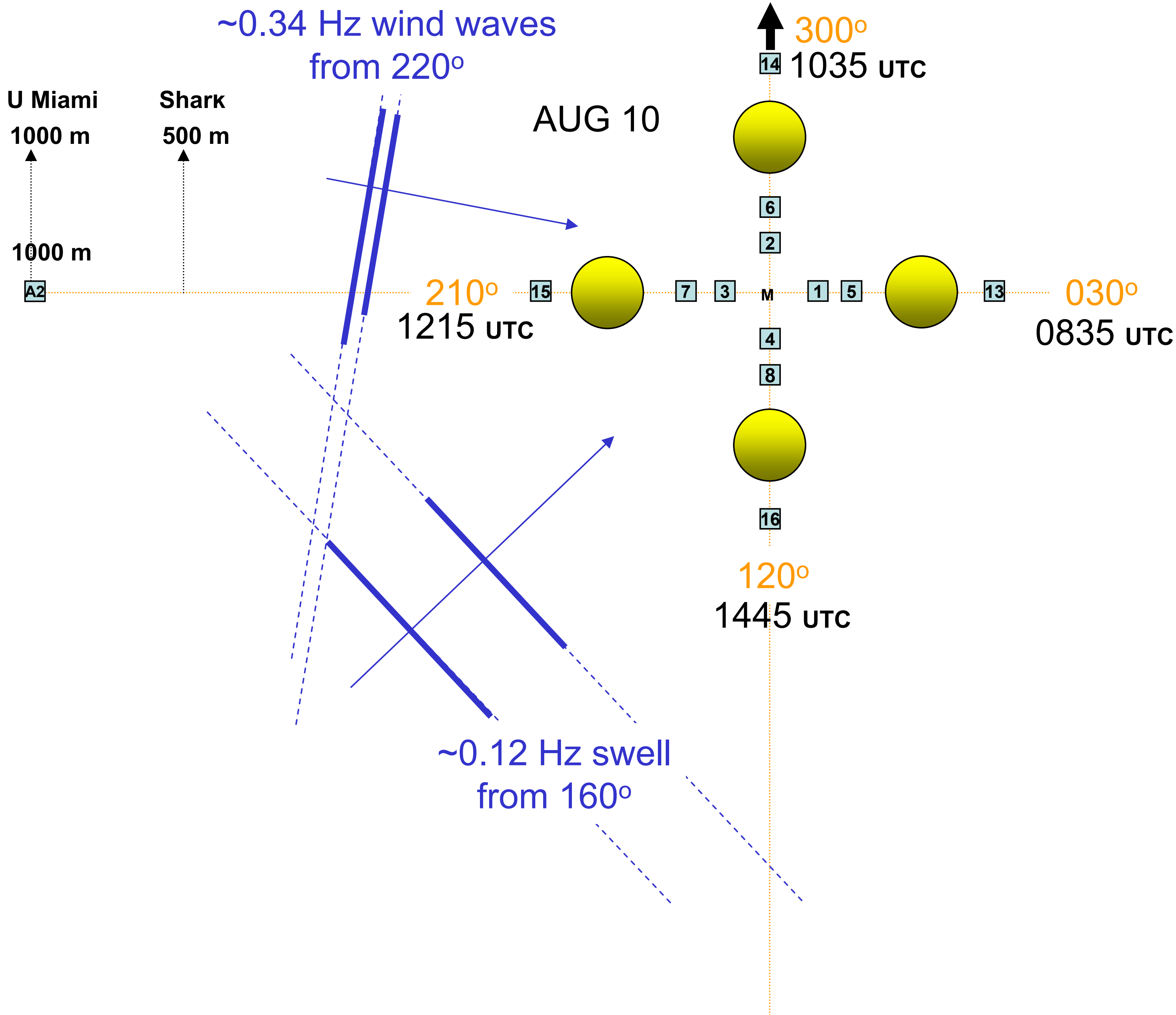
$$\Gamma_{xy} = \frac{\langle xy^* \rangle}{\sqrt{\langle xx^* \rangle \langle yy^* \rangle}}$$

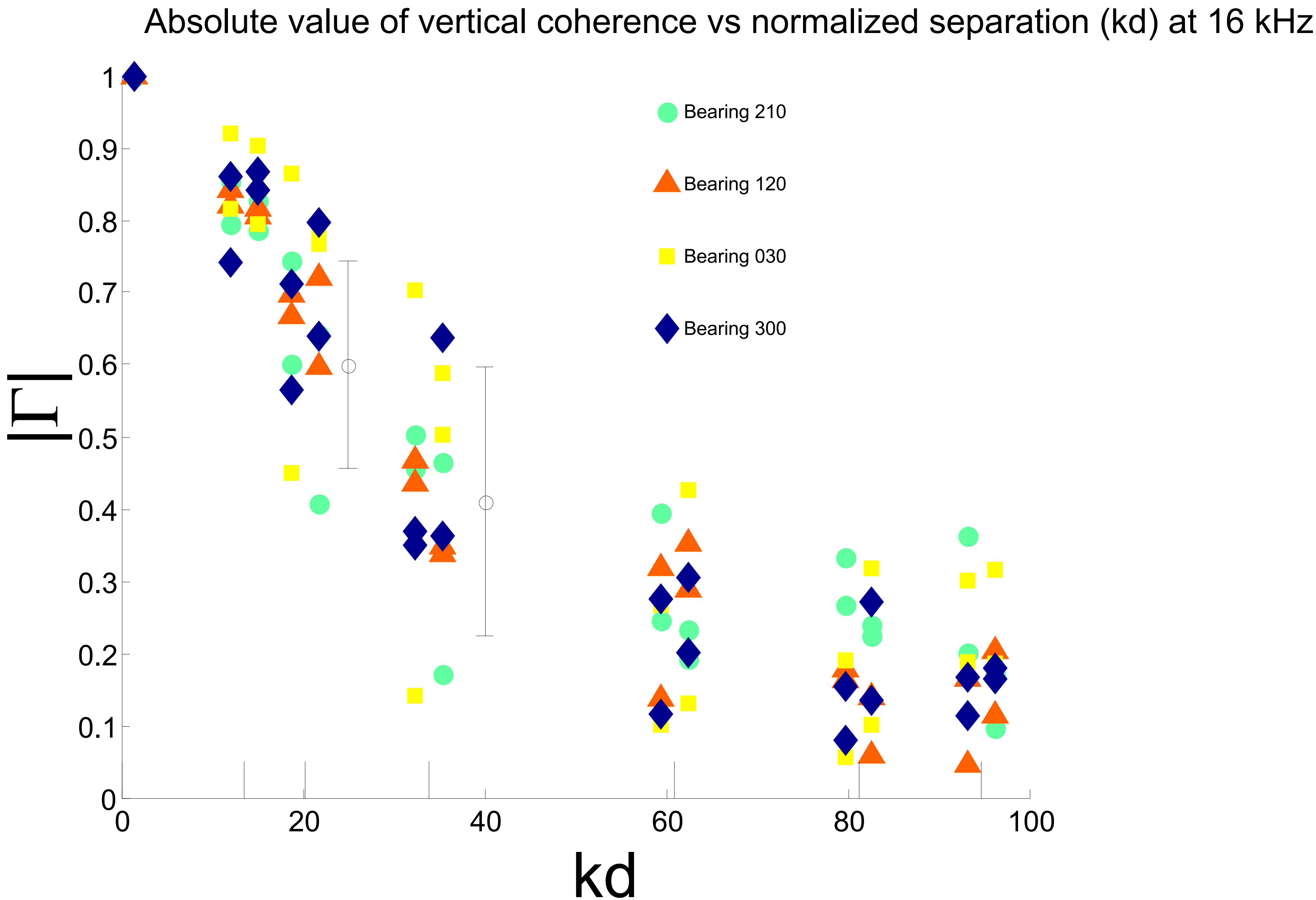
4 receiver pairs and frequency (k)
6 combinations of kd

Average air-sea conditions for 0830-1500 UTC. Wind speed 6 m/s +/- 1 m/s

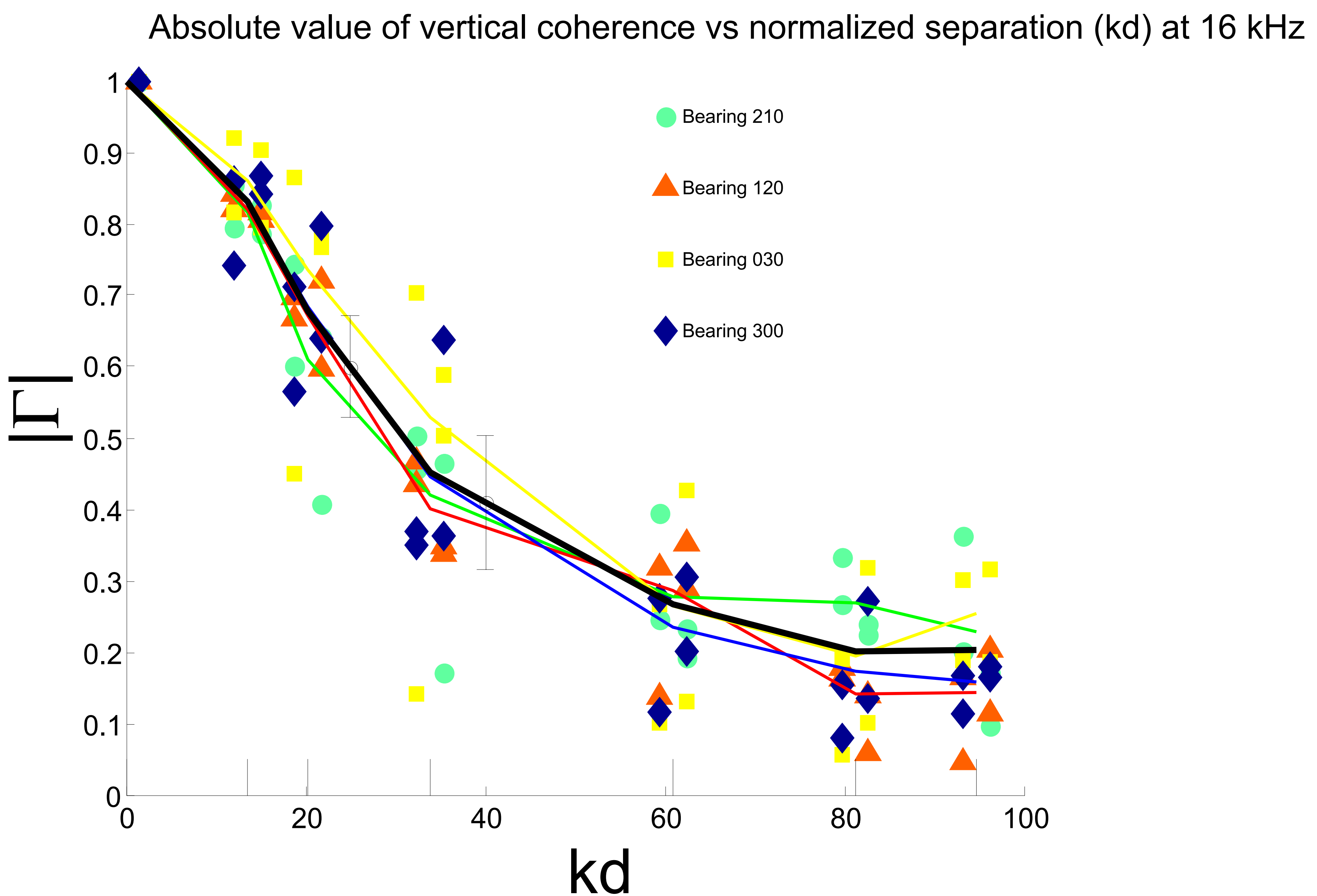





~0.34 Hz wind waves
from 220°
U Miami
1000 m
Shark
500 m
1000 m
A2
AUG 10
300°
14
1035 UTC
6
2
210°
15
7
3
M
1
5
13
030°
1215 UTC
0835 UTC
4
8
16
120°
1445 UTC
~0.12 Hz swell
from 160°



Absolute value of vertical coherence vs normalized separation (kd) at 16 kHz
Bearing 210
Bearing 120
Bearing 030
Bearing 300
|Γ|
kd
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100



Absolute value of vertical coherence vs normalized separation (kd) at 16 kHz
Bearing 210
Bearing 120
Bearing 030
Bearing 300
|Γ|
kd
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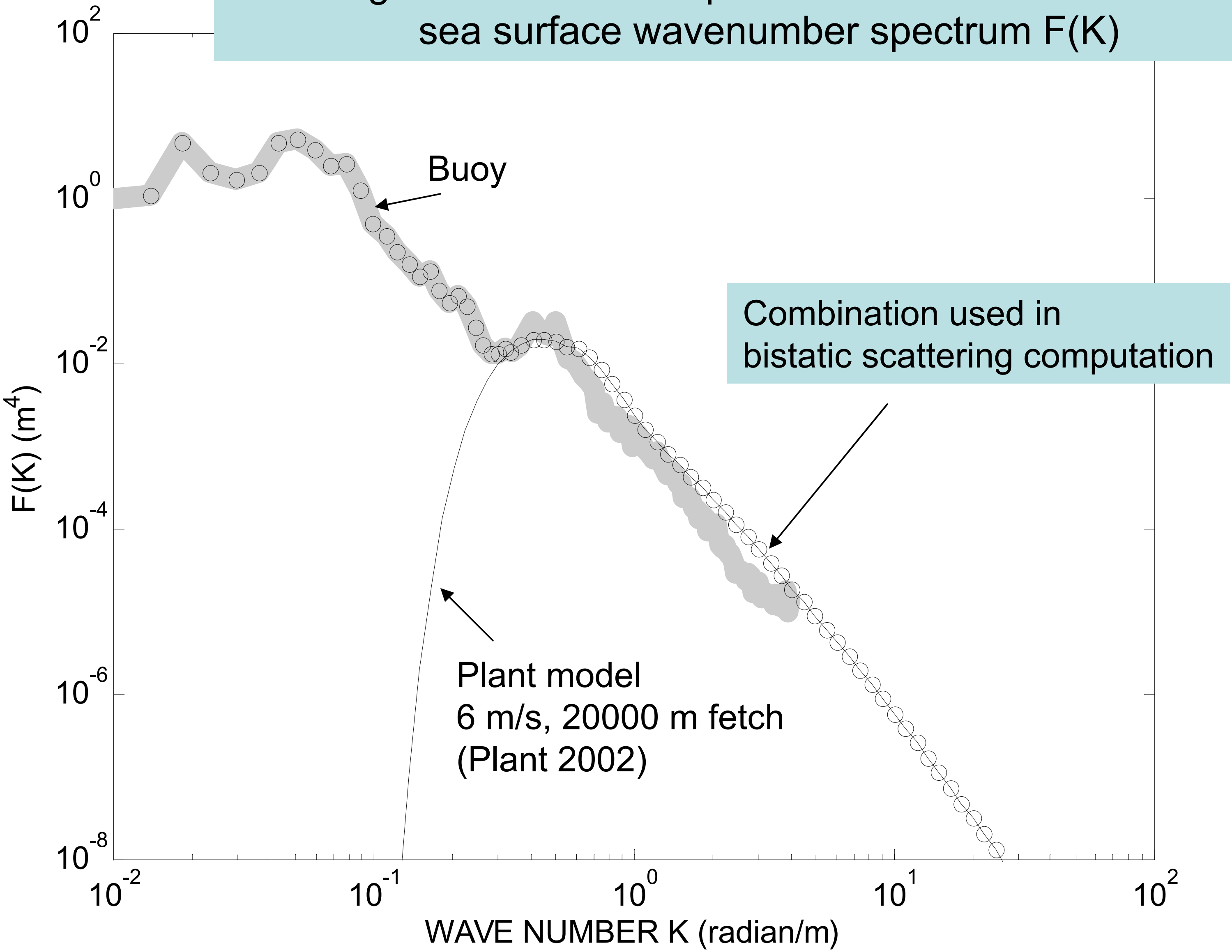
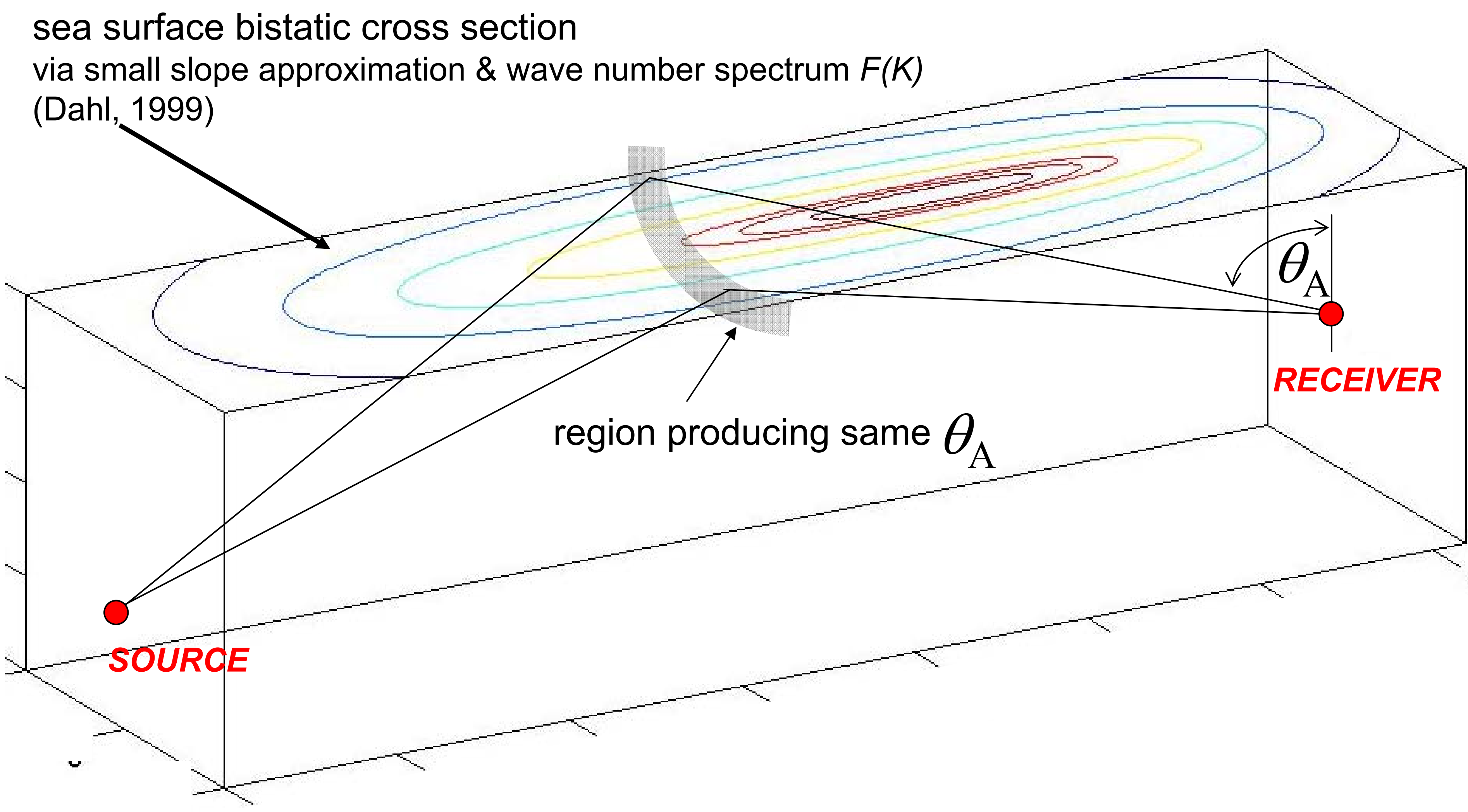
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100

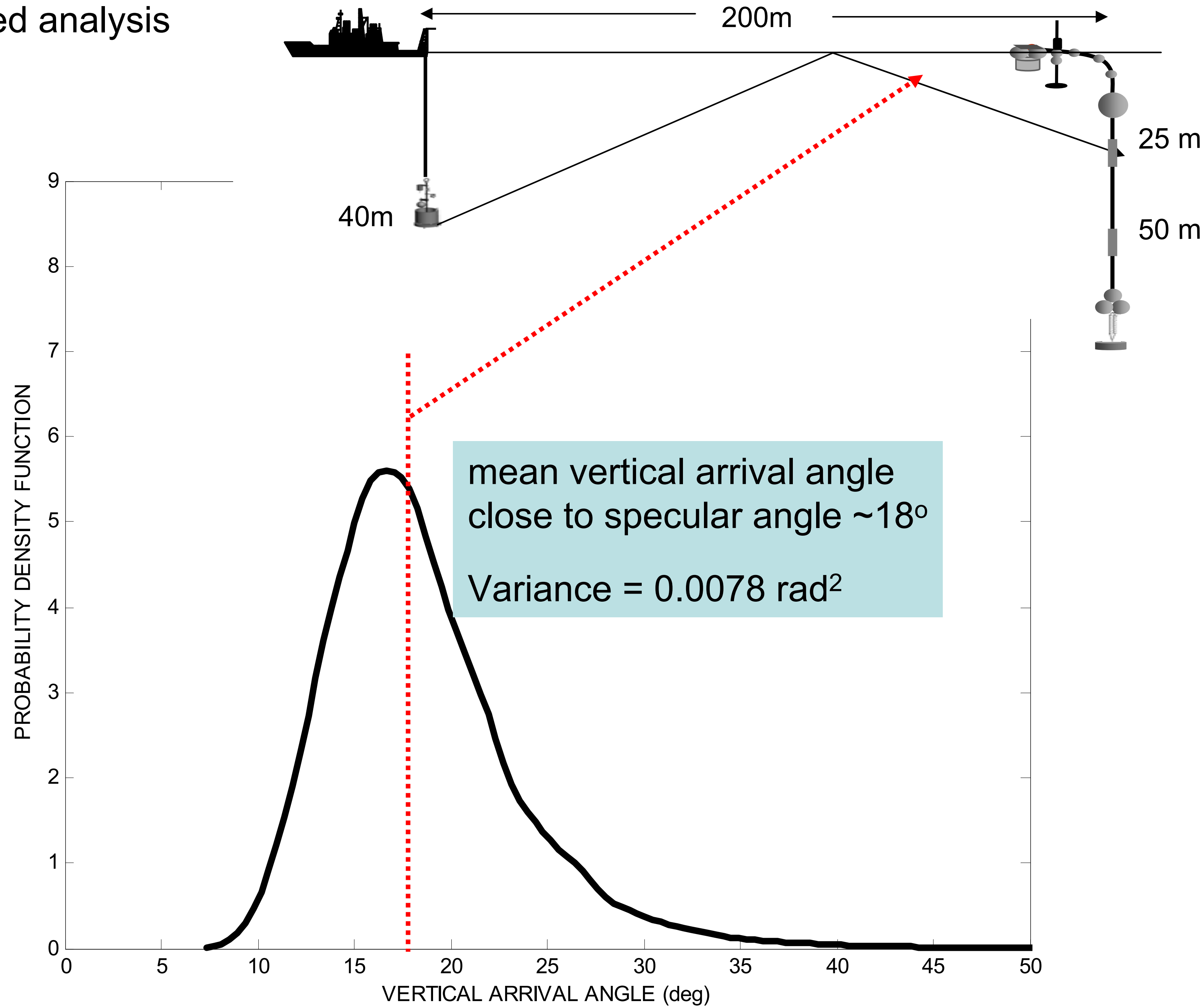
Modeling of coherence will proceed with directional-averaged sea surface wavenumber spectrum F(K)



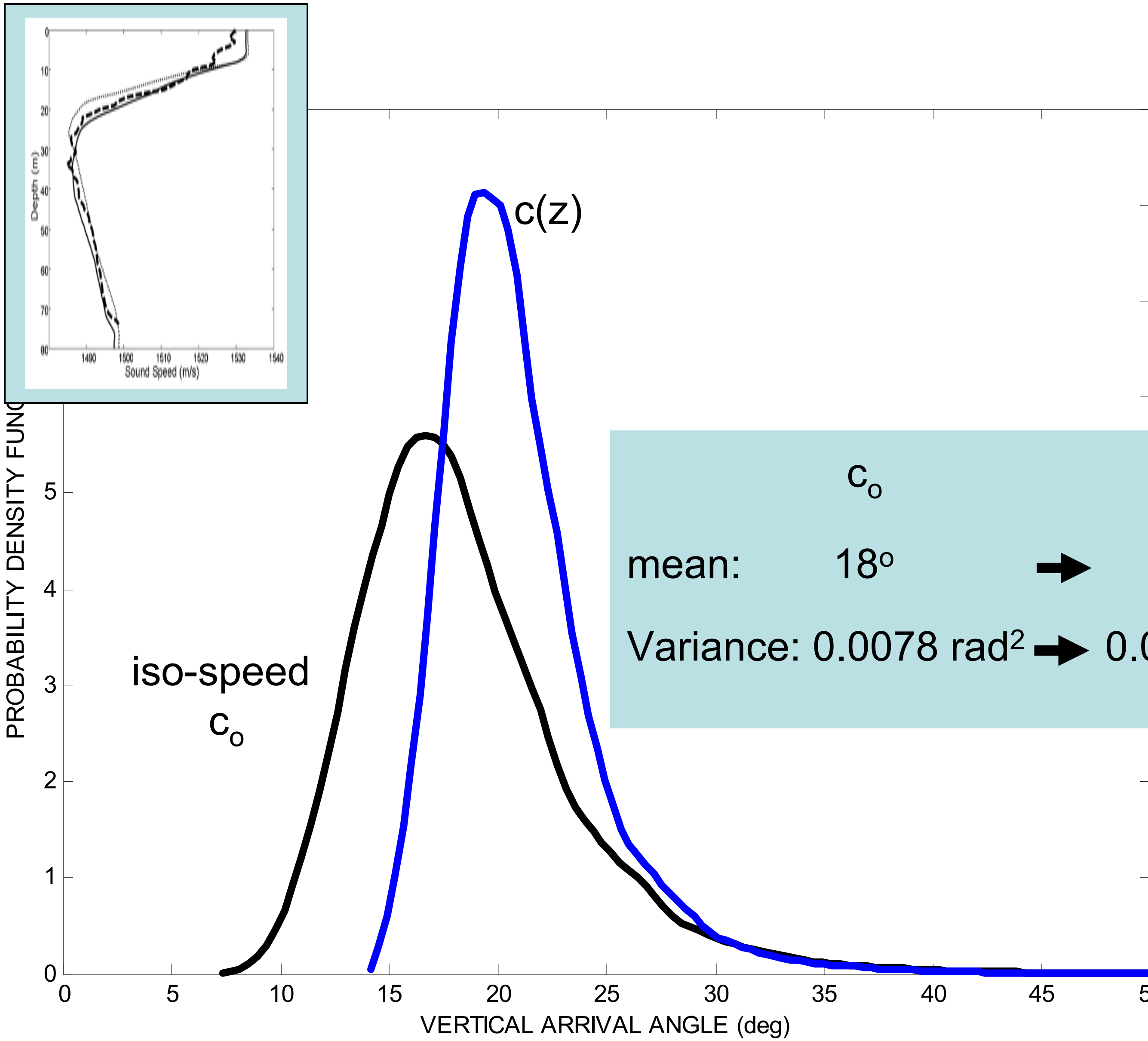
PDF for vertical arrival angle



iso-speed analysis



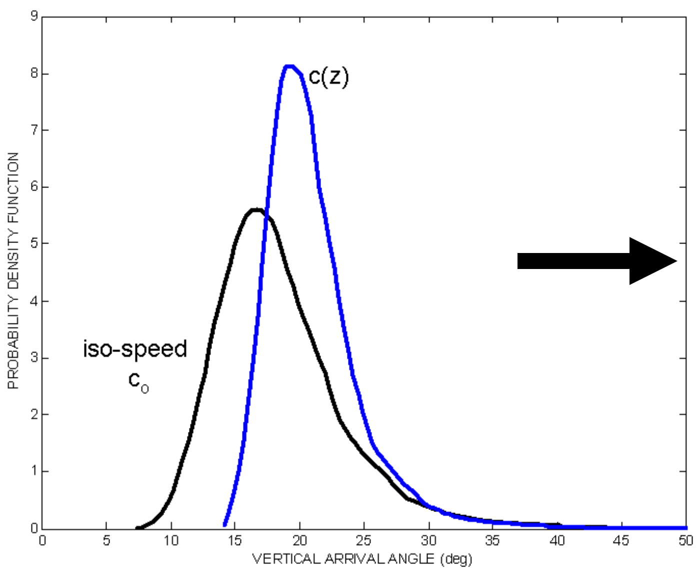
Analysis using measured c(z) with thermocline

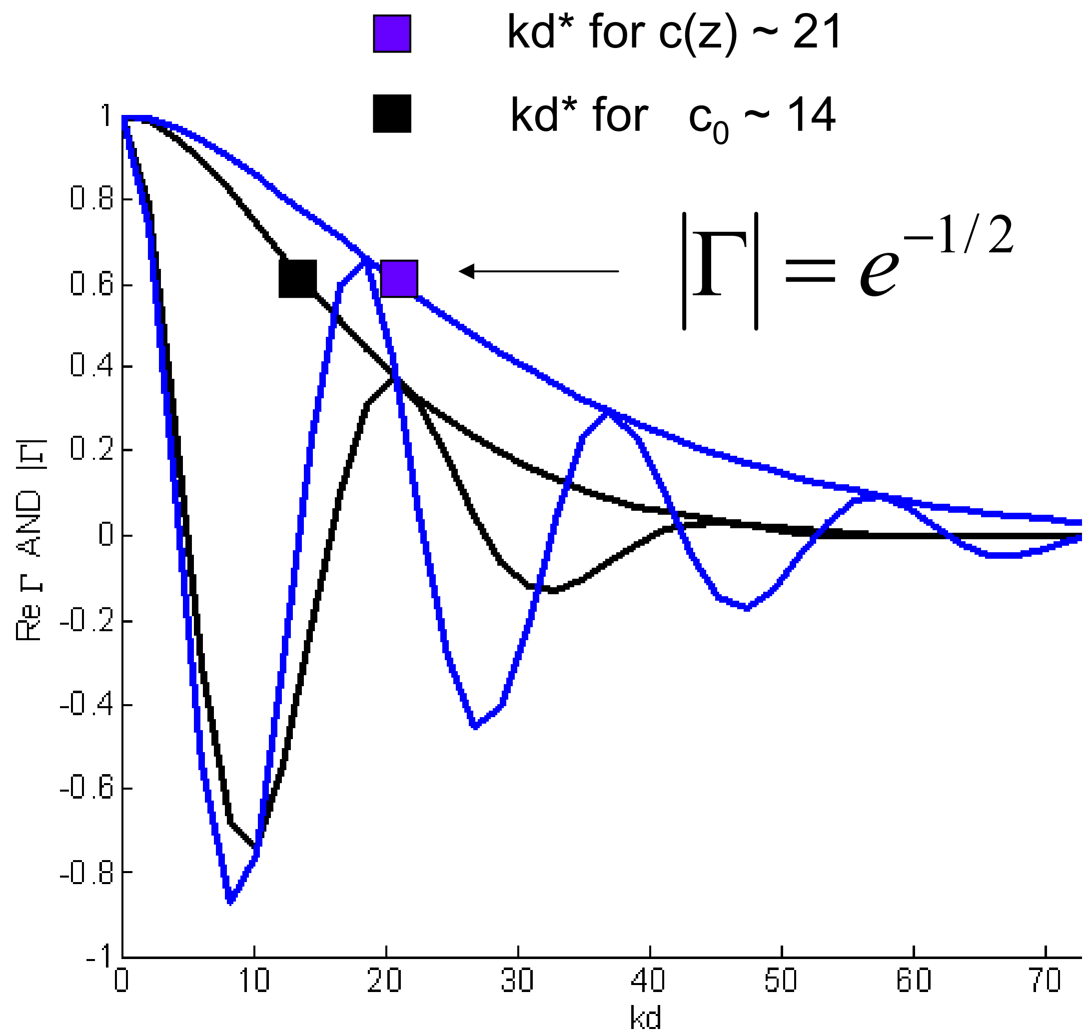


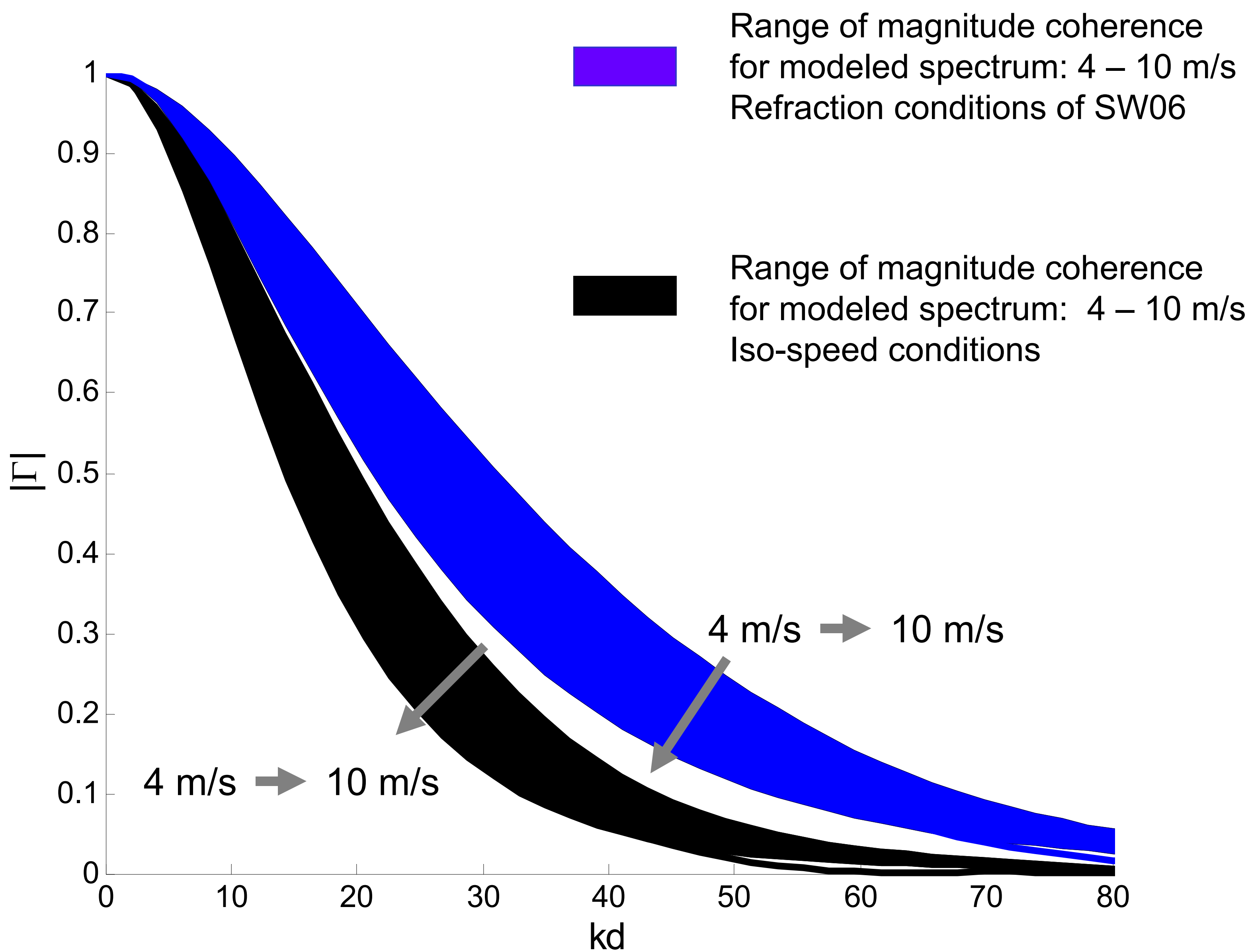
	c_o		$c(z)$
mean:	18^o	→	21^o
Variance:	0.0078 rad^2	→	0.0042 rad^2

The PDF for vertical arrival angle is readily converted to spatial coherence Γ(kd)

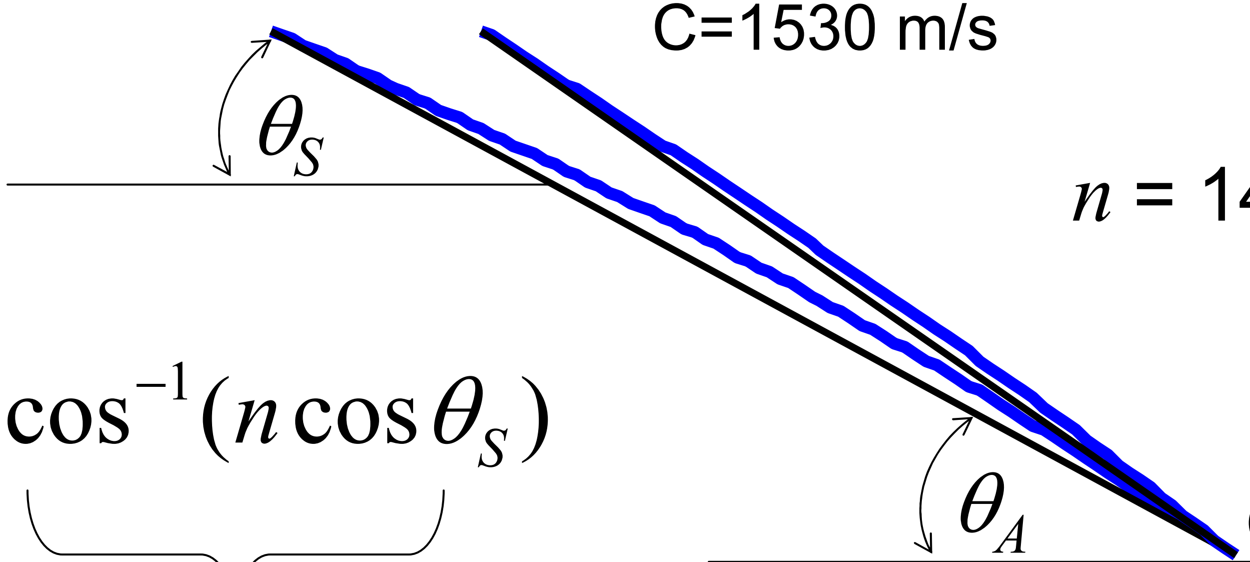
Alternatively, the van Cittert-Zernike Theorem can utilized to estimate Γ(kd)
(Dahl 2002, 2004)







Range of magnitude coherence
for modeled spectrum: 4 – 10 m/s
Refraction conditions of SW06
Range of magnitude coherence
for modeled spectrum: 4 – 10 m/s
Iso-speed conditions
4 m/s
10 m/s
4 m/s
10 m/s
|Γ|
kd
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80



n = 1485/1530

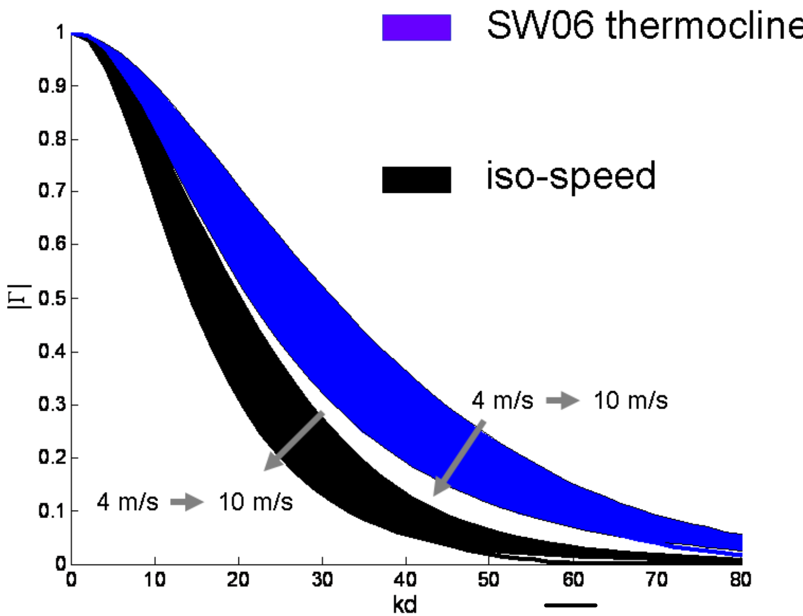
$$\theta_A = \cos^{-1}(n\cos\theta_S)$$

f is a smooth function relating surface-to-arrival angle

$$\therefore \quad \mathrm{var}(\theta_A) \approx \left(\frac{\partial f}{\partial \theta_S}\Big|_{\bar{\theta}_S}\right)^2 \mathrm{var}(\theta_S)$$

Vertical angular compression factor $\boxed{\dfrac{-n\sin(\bar{\theta}_S)}{\sqrt{1-n^2\cos^2\bar{\theta}_S}}}$

Vertical Angular Compression



Large change in kd* predicted by the angular compression factor

Compression does *not* $\Rightarrow \uparrow$ intensity

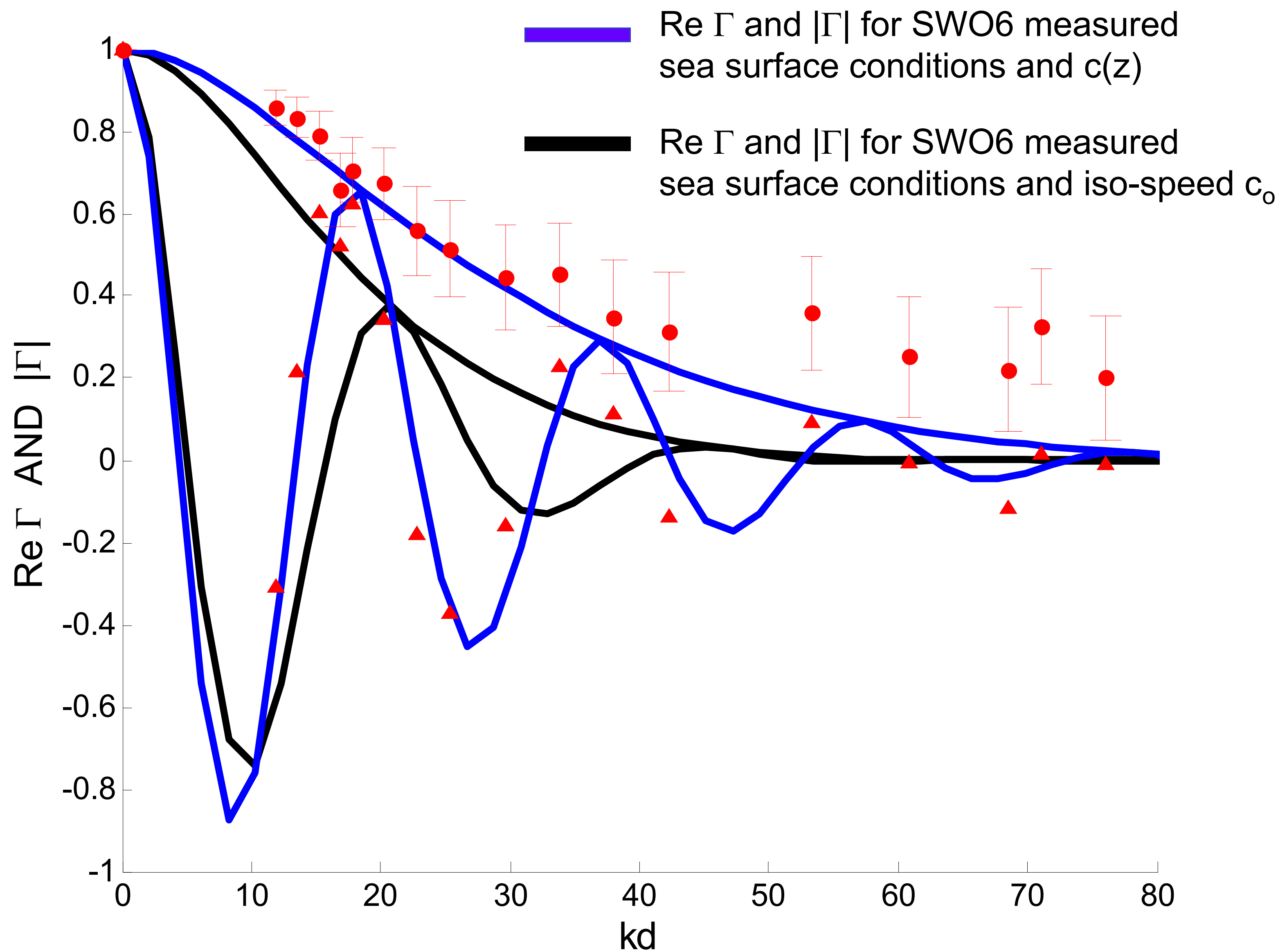
SW06 geometry:
TL *increased* by 1.5 dB (confirmed by ray and PE analysis)

$$\underset{\text{SW06 thermocline}}{\sigma_{\theta_A}} = \frac{n\sin(\bar{\theta}_S)}{\sqrt{\underbrace{1-n^2\cos^2\bar{\theta}_S}_{\boxed{0.72}}}}\;\underset{\text{iso-speed}}{\sigma_{\theta_A}}$$

$$\boxed{kd^* \sim 1/\sigma_{\theta_A}}$$

$$\boxed{\therefore\ kd^*_{\text{should}} \uparrow \text{ by} \sim 4/3}$$

Model comparison with data (14-16-18-20 kHz) plotted verus kd



Summary

•Spatial coherence in sea surface forward scattering with strong thermocline

•Vertical angular compression: dominate effect greater than that linked to sea surface roughness and slope

•Vertical angles *compressed* while TL *increased* over spherical spreading
(angle expansion in upward paths not balanced by downward paths)

•Mild refraction effects (influencing phase of Γ) observed in ASIAEX data (Dahl 2004)
SWO6: strong refraction effects influencing both magnitude and phase

•Predictive model based on Snell's mapping of angular variances