The Evolution of Vertical Spatial Coherence with Range from Source

Peter H. Dahl

Applied Physics Laboratory and Mechanical Engineering Dept.

University of Washington

Dajun Tang

Applied Physics Laboratory, University of Washington

Jee Woong Choi

Hanyang University, Ansan Korea

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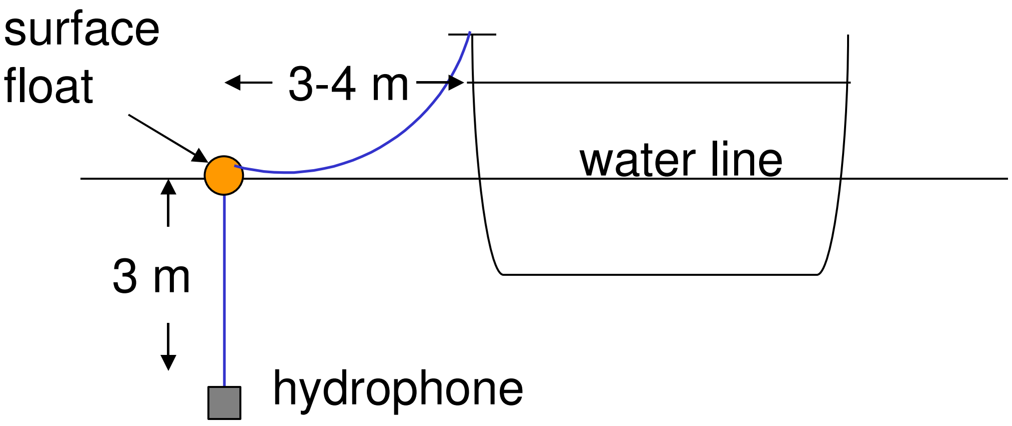
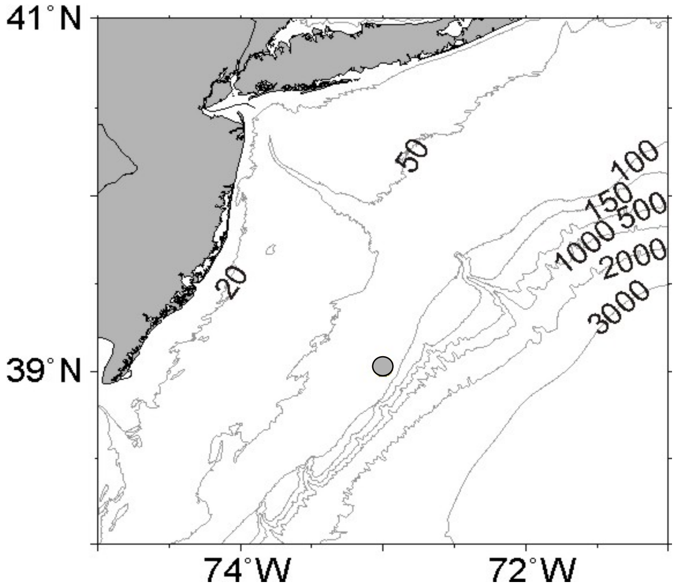
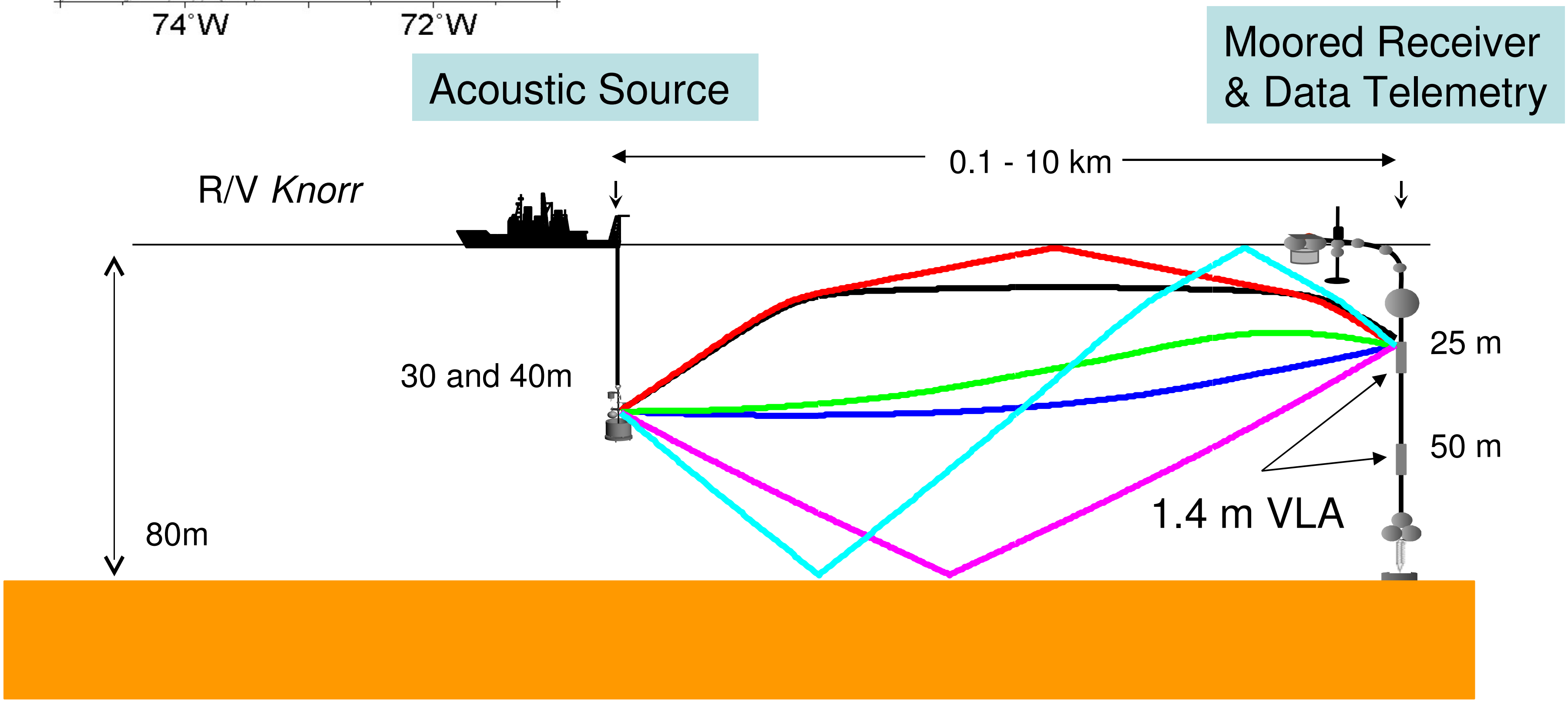
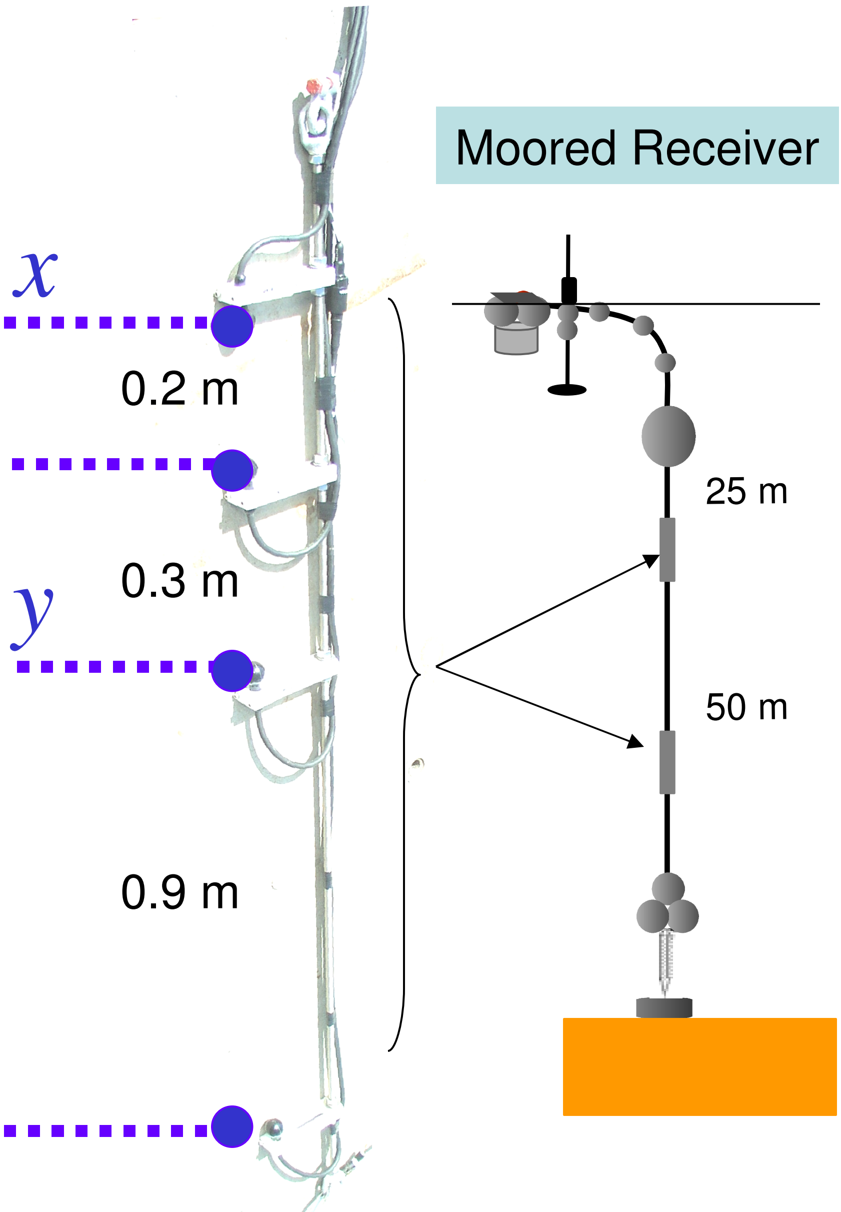

surface
float
3-4 m
water line
3 m
hydrophone



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

Shallow Water 06 (SW06) August 2006





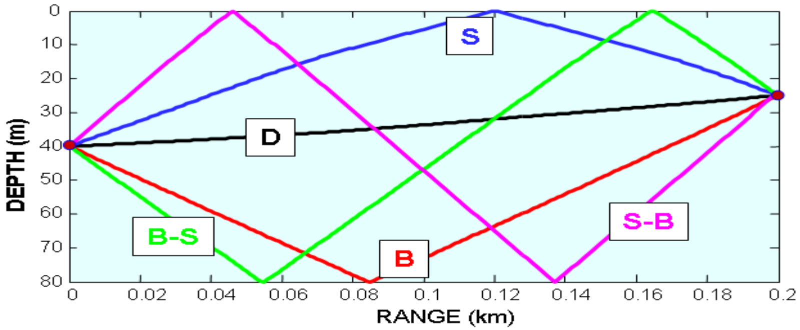
Spatial coherence between (d) vertically-separated channels based on N ping avg

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

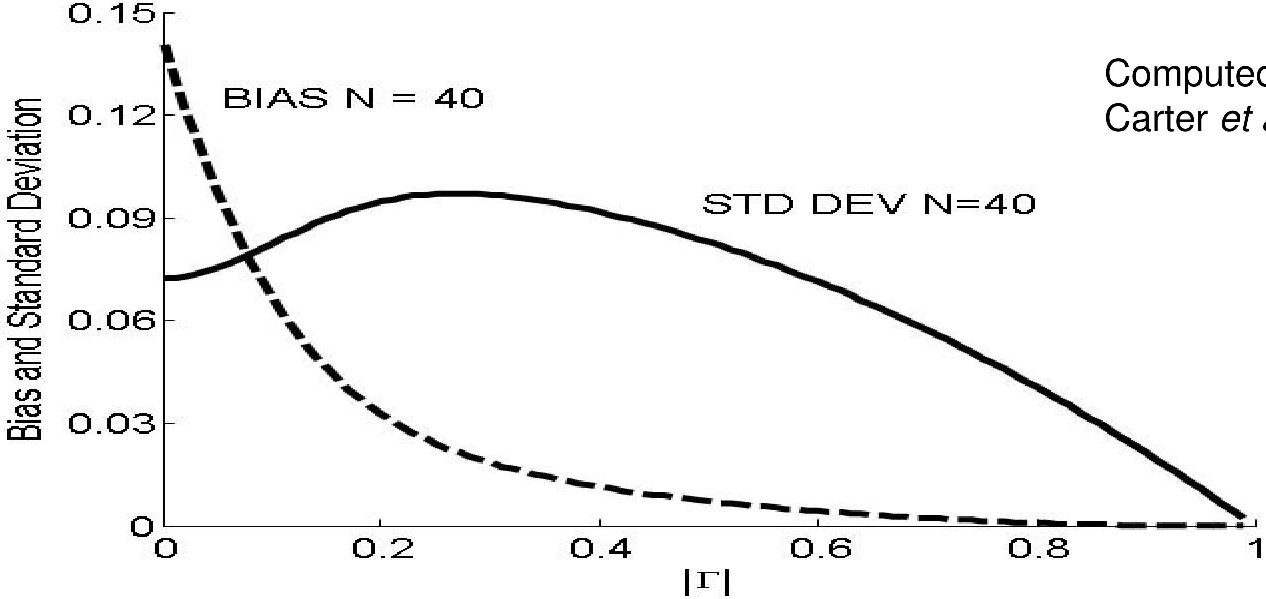
4 receiver pairs and frequency (k)
6 combinations of kd

MEASUREMENT APPROACH

Estimates of vertical spatial coherence made with FM and CW pulses
- frequencies 3-18 kHz
- BW << 1/channel impulse time, multi-paths are not separated but combined



Each pulse separated by ~60 sec.
Considerable averaging necessary to reduce both bias and variance.



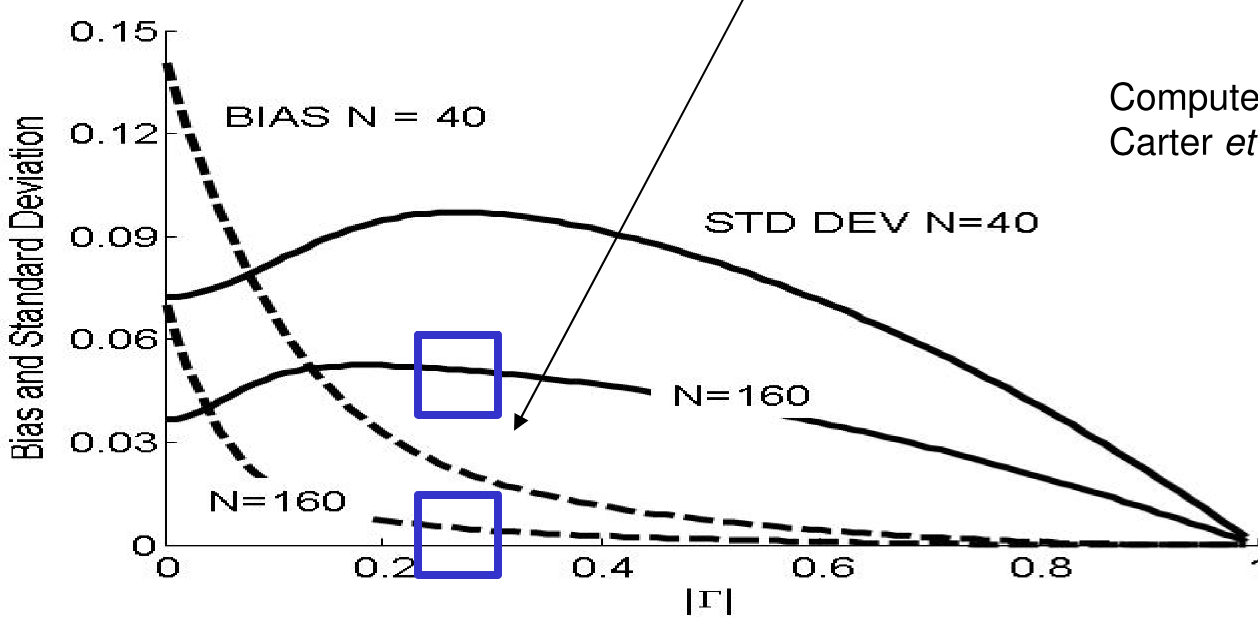
Computed from equations in Carter *et al*. (1973)

MEASUREMENT APPROACH

Low values of coherence magnitude particularly susceptible to bias

Several experimental sets combined over periods of order 60 min. is sufficient to reduce bias and variance to acceptable levels – especially important for lower magnitudes of coherence < ~0.3

For N~100 or more estimates, more tolerable bias and variance for low coherence magnitudes



Computed from equations in Carter *et al*. (1973)

MODELING APPROACH

RAM Parabolic Equation (Collins) modified to account for rough water-air impedance boundary (via approach of Thomson and Brooke, 2003)

Generate 1-D cuts through a 2-D sea surface:

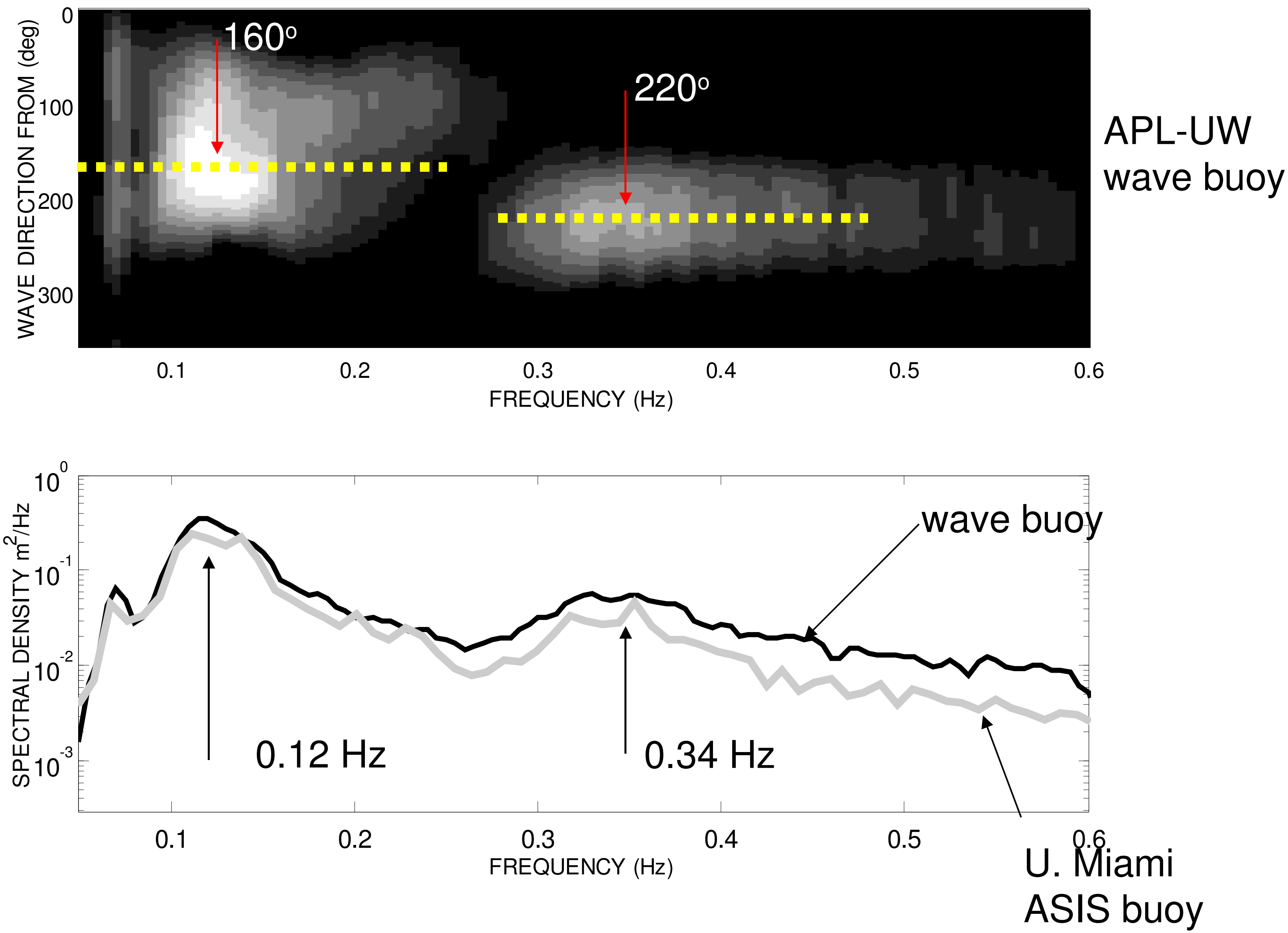
Large surface wavelengths ($\lambda > 16$ cm, $|K| < 1$) use directional information from nearby wave buoy estimates (Low Pass Sea Surface)

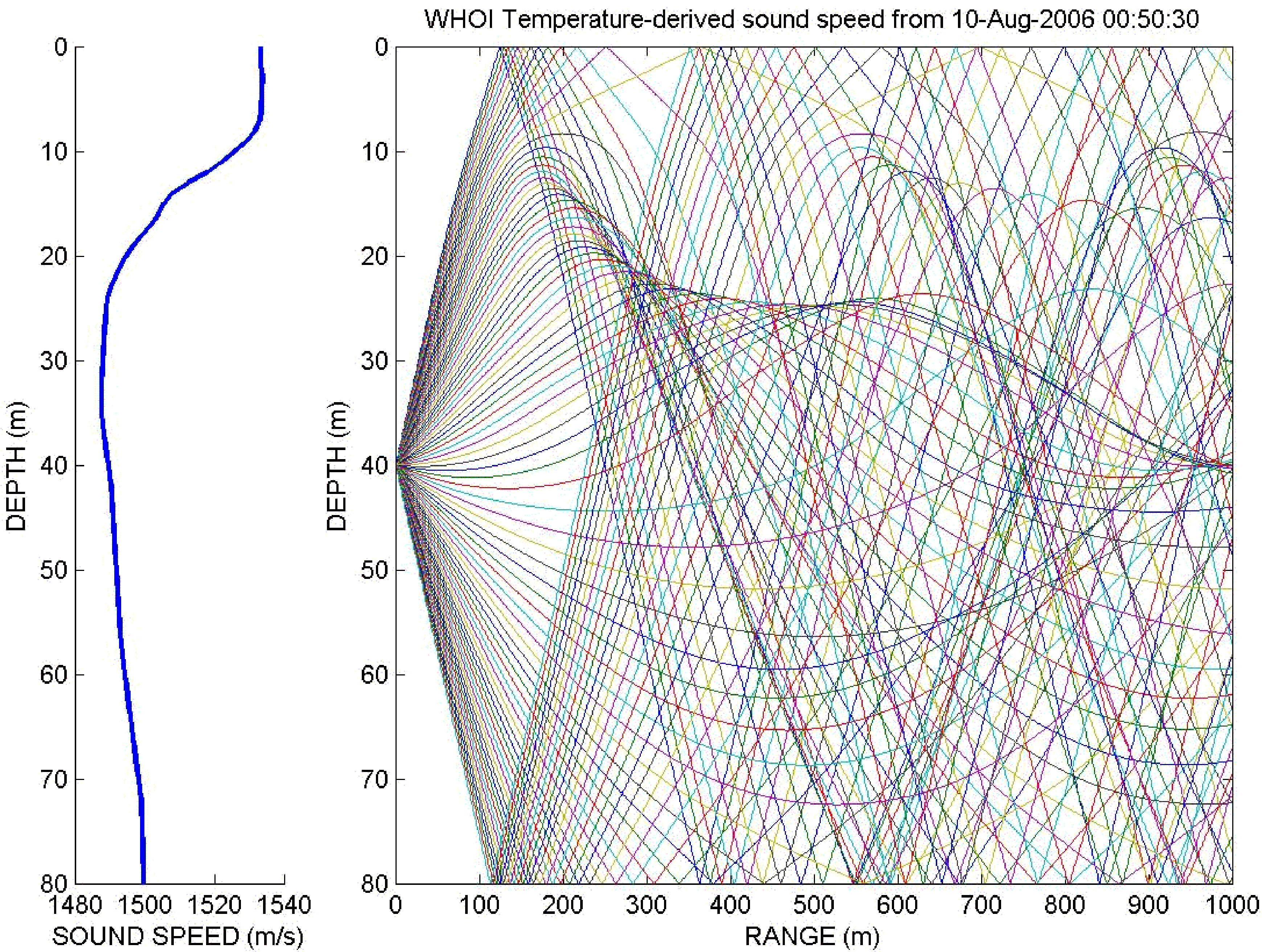
Small surface wavelengths ($|K| > 1$) goes as $1/|K_x|^{-3}$ equivalent to $1/|K|^{-4}$ in 2D (High Pass Sea Surface)

Surface Realization = Low Pass + High Pass   with wave number support up to K~ 30

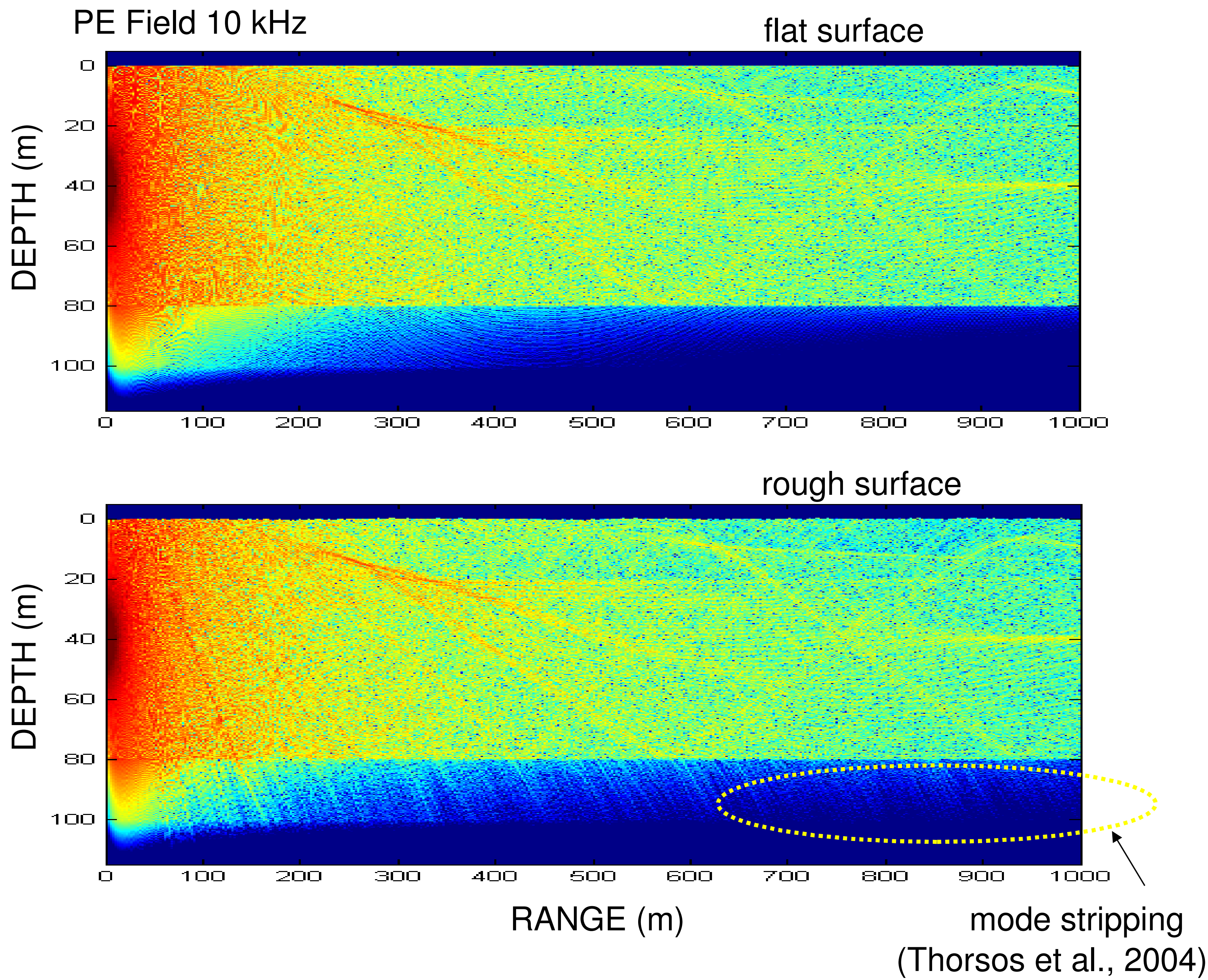
Sound speed data taken when appropriate from with CTD casts made from the R/V Knorr, or derived from he WHOI temperature mooring (“Shark”)

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

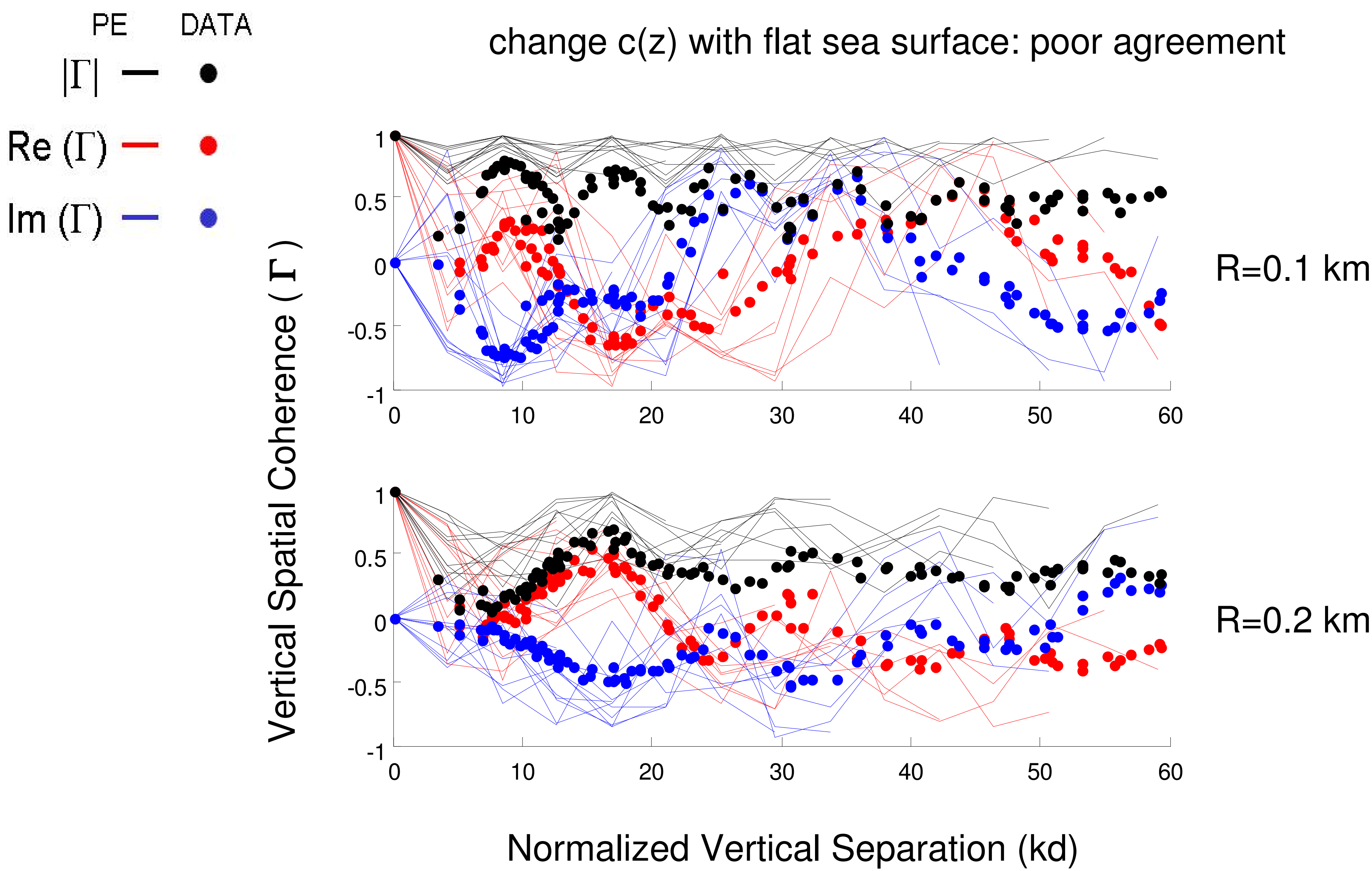




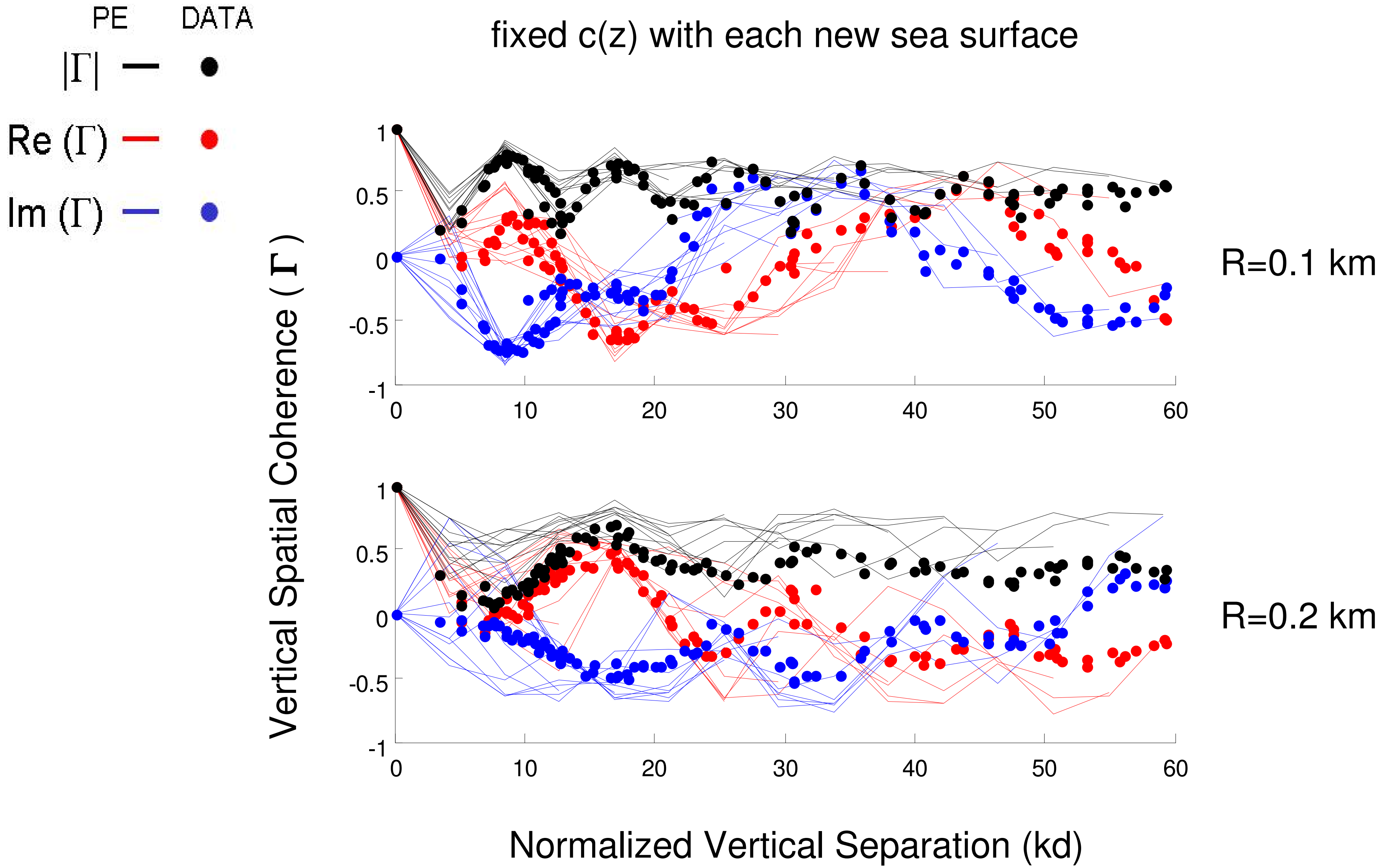
WHOI Temperature-derived sound speed from 10-Aug-2006 00:50:30
DEPTH (m)
SOUND SPEED (m/s)
1480 1500 1520 1540
0 10 20 30 40 50 60 70 80
DEPTH (m)
RANGE (m)
0 100 200 300 400 500 600 700 800 900 1000



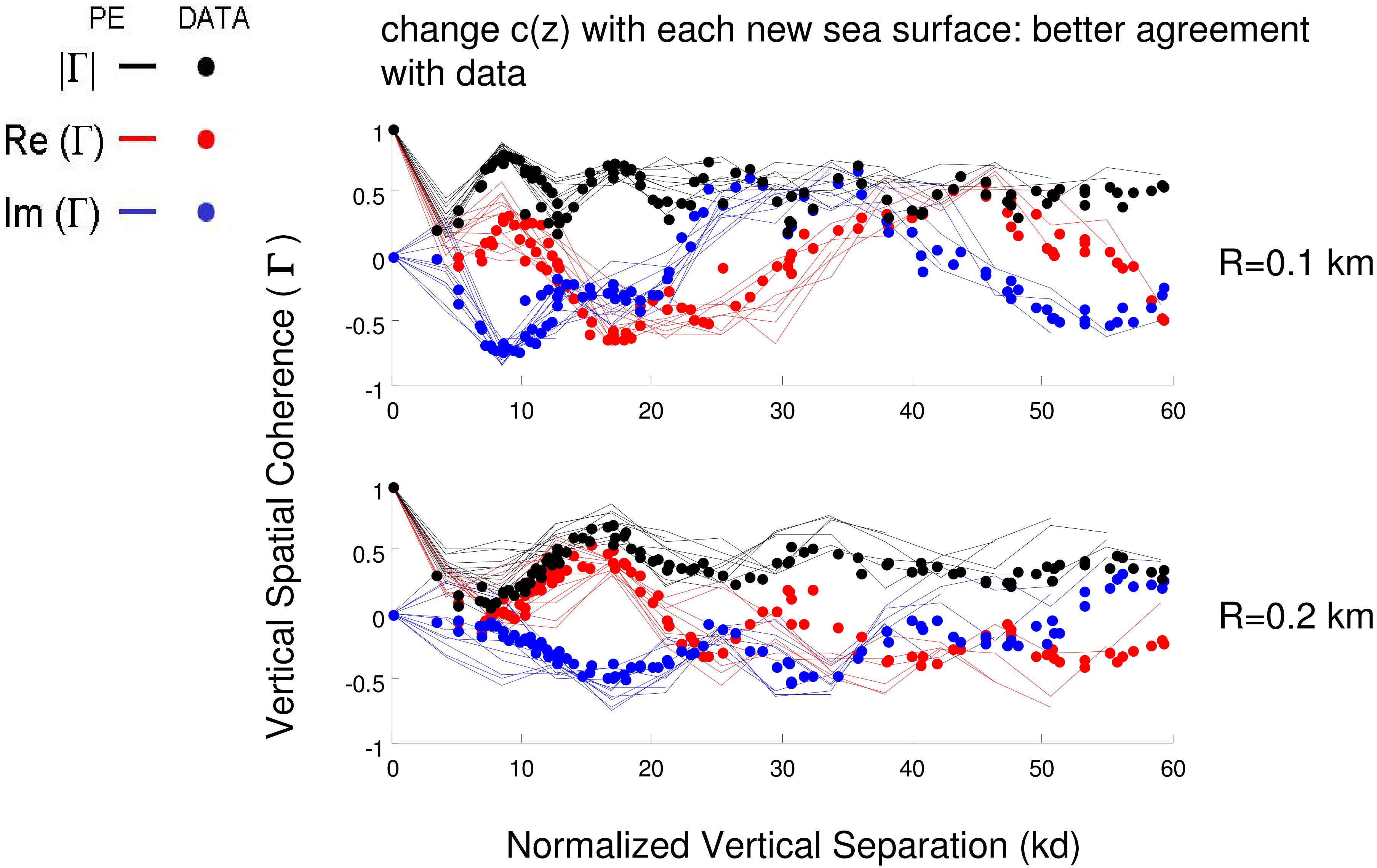
PE Field 10 kHz
flat surface
DEPTH (m)
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800
900
1000
rough surface
DEPTH (m)
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800
900
1000
RANGE (m)
mode stripping
(Thorsos et al., 2004)

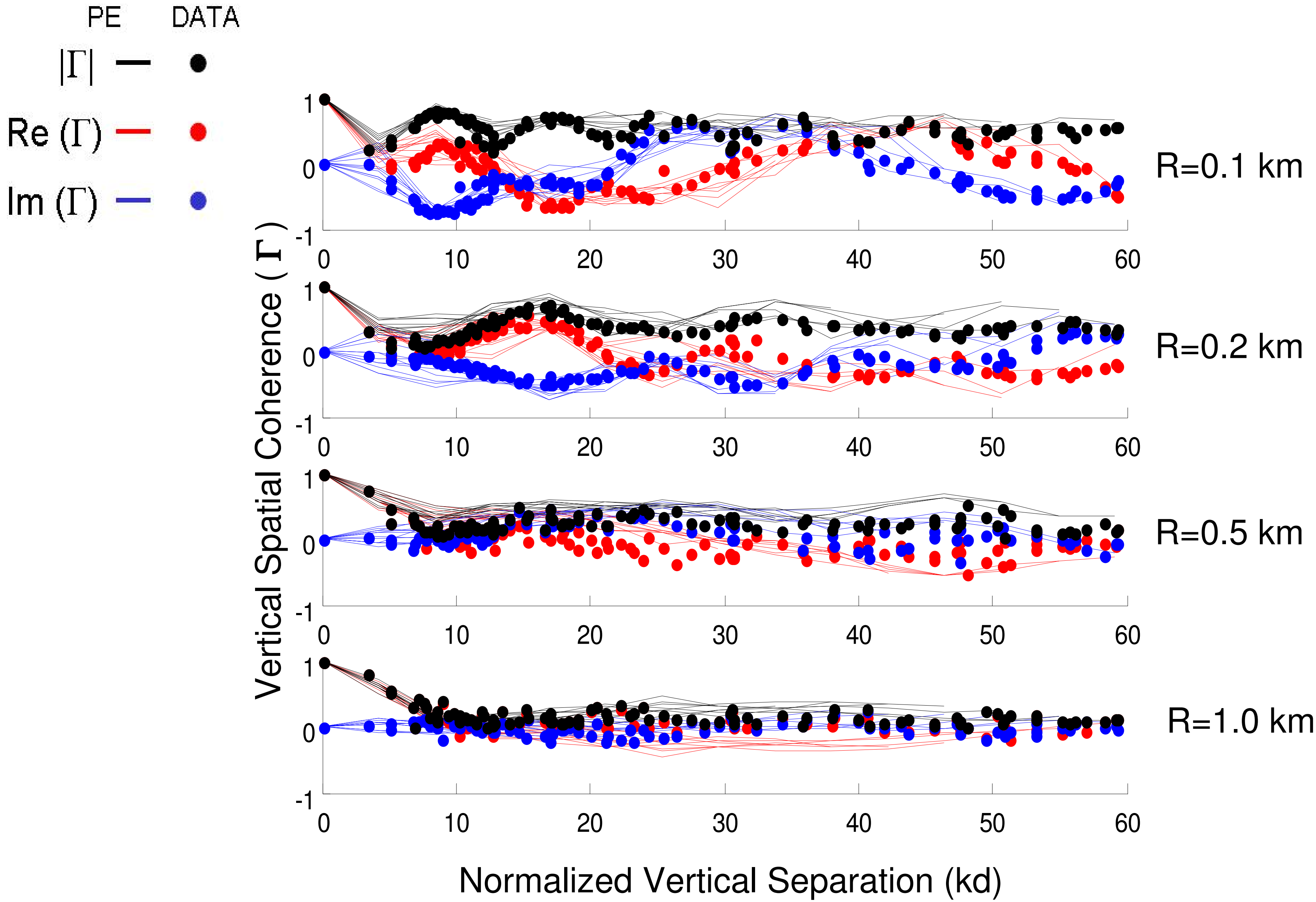


PE
DATA
|Γ|
Re (Γ)
Im (Γ)
change c(z) with flat sea surface: poor agreement
R=0.1 km
R=0.2 km
Vertical Spatial Coherence (Γ)
Normalized Vertical Separation (kd)
1
0.5
0
-0.5
-1
0
10
20
30
40
50
60

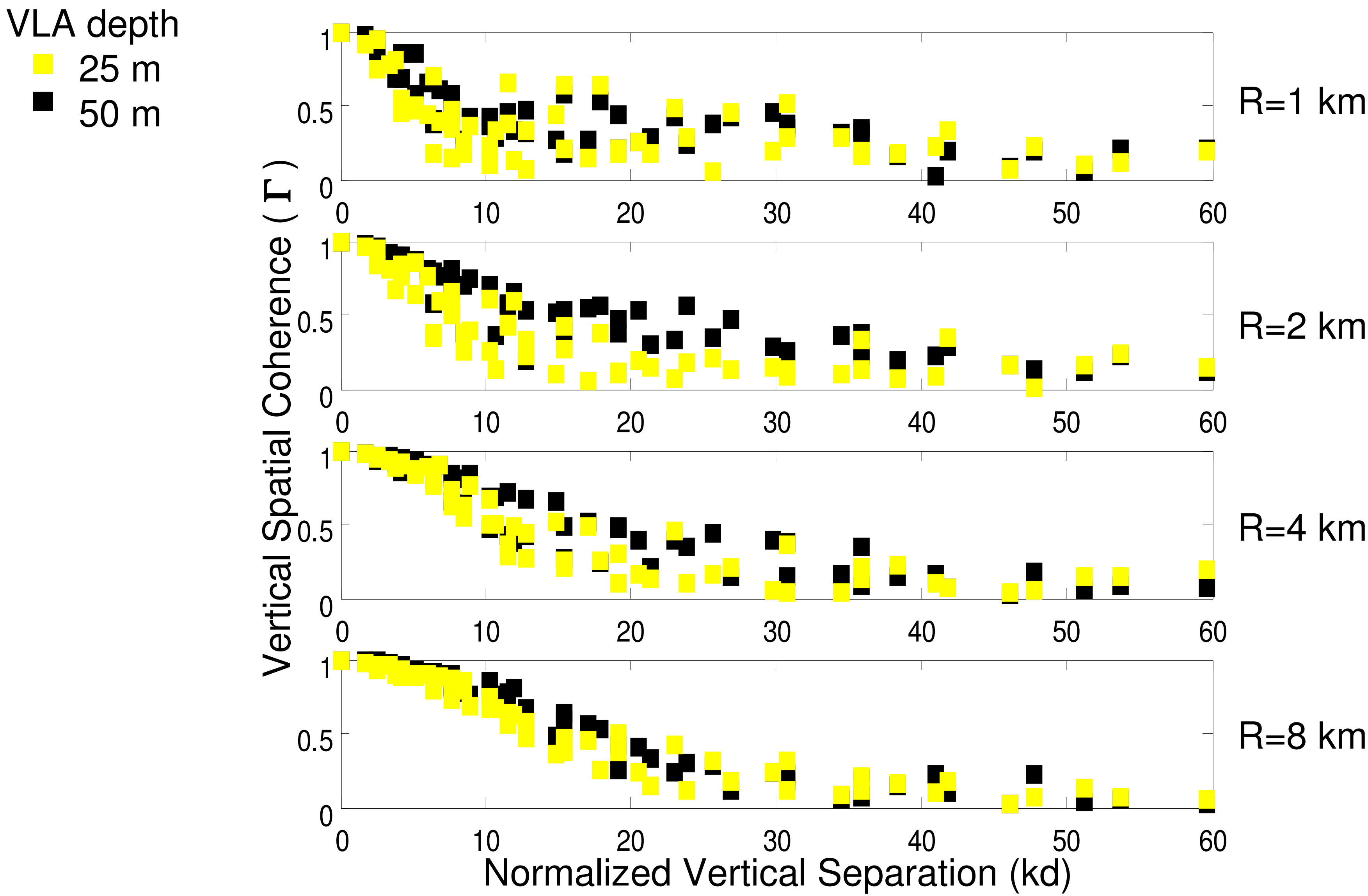

PE
DATA
$|\Gamma|$
Re (Γ)
Im (Γ)
fixed c(z) with each new sea surface
Vertical Spatial Coherence (Γ)
R=0.1 km
R=0.2 km
1
0.5
0
-0.5
-1
0
10
20
30
40
50
60
Normalized Vertical Separation (kd)

change c(z) with each new sea surface: better agreement with data

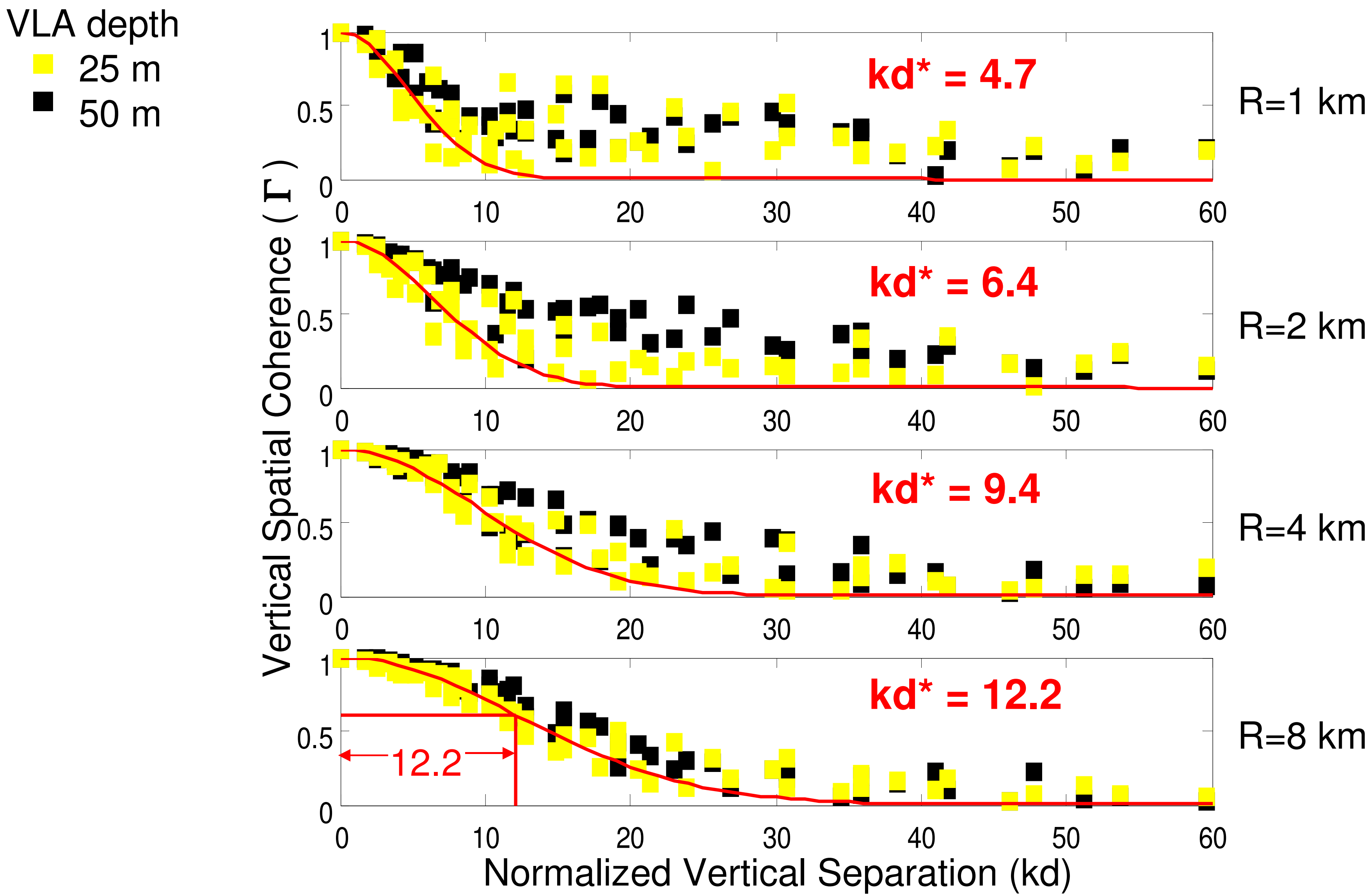




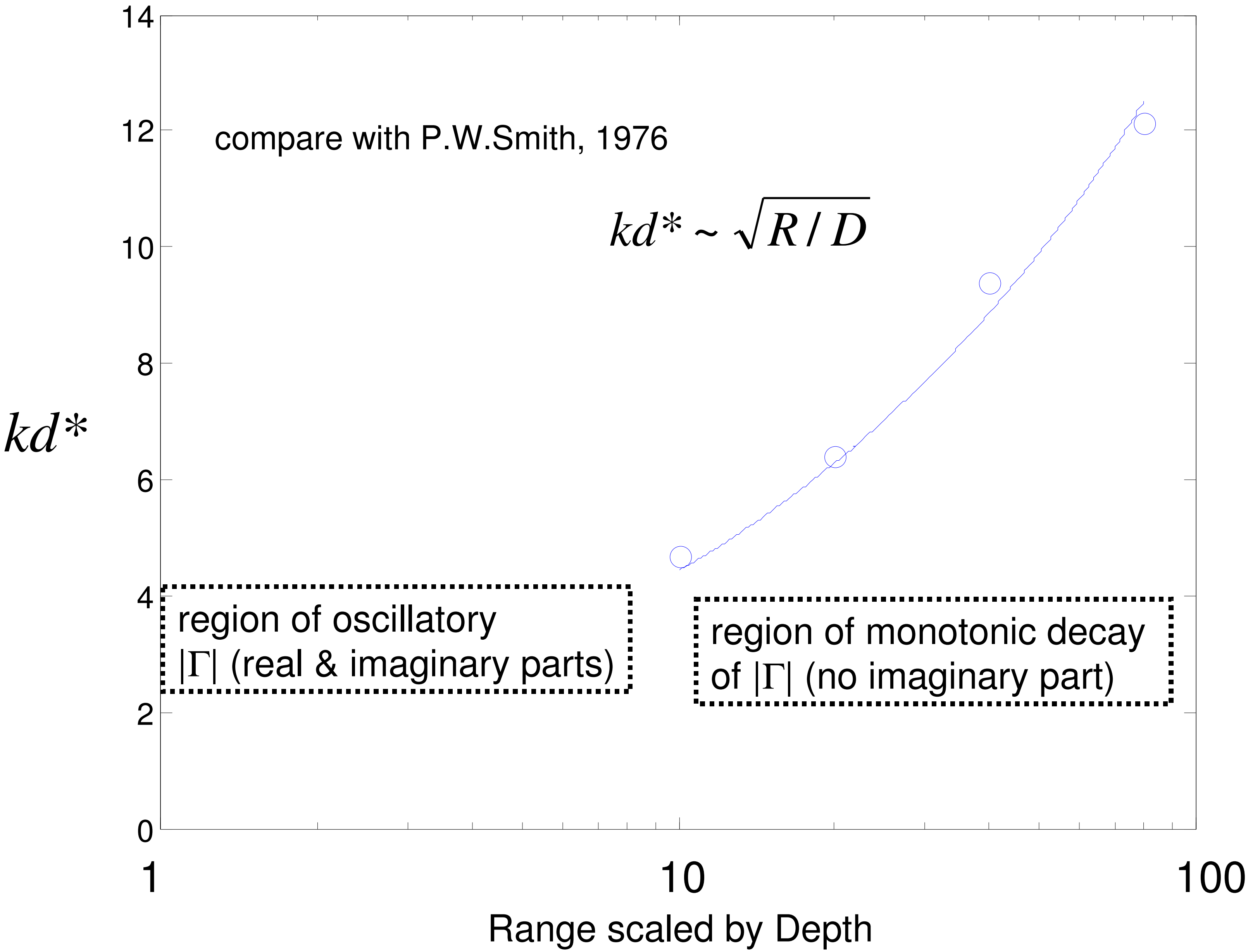
PE
DATA
|Γ|
Re (Γ)
Im (Γ)
R=0.1 km
R=0.2 km
R=0.5 km
R=1.0 km
Vertical Spatial Coherence (Γ)
Normalized Vertical Separation (kd)



VLA depth
25 m
50 m
Vertical Spatial Coherence (Γ)
R=1 km
R=2 km
R=4 km
R=8 km
0
0.5
1
0
10
20
30
40
50
60
Normalized Vertical Separation (kd)



VLA depth
25 m
50 m
kd* = 4.7
R=1 km
kd* = 6.4
R=2 km
kd* = 9.4
R=4 km
kd* = 12.2
R=8 km
12.2
Vertical Spatial Coherence (Γ)
Normalized Vertical Separation (kd)
0
0.5
1
0
10
20
30
40
50
60



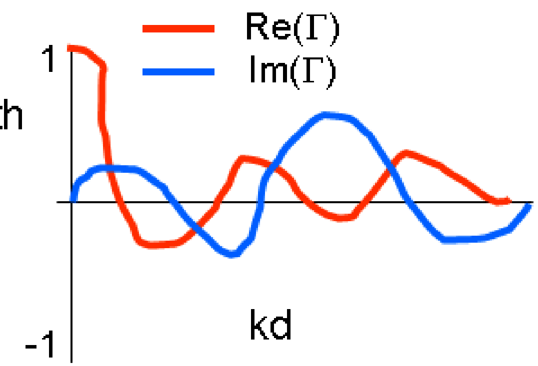
compare with P.W.Smith, 1976
$kd^* \sim \sqrt{R/D}$
kd^*
region of oscillatory
$|\Gamma|$ (real & imaginary parts)
region of monotonic decay
of $|\Gamma|$ (no imaginary part)
Range scaled by Depth
0
2
4
6
8
10
12
14
1
10
100

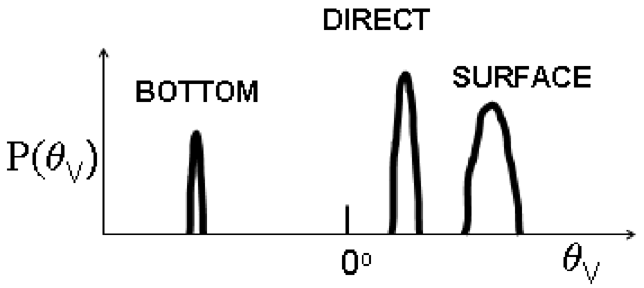
Notional Ideas on Vertical Coherence

VERTICAL COHERENCE | VERTICAL ANGULAR SPREAD

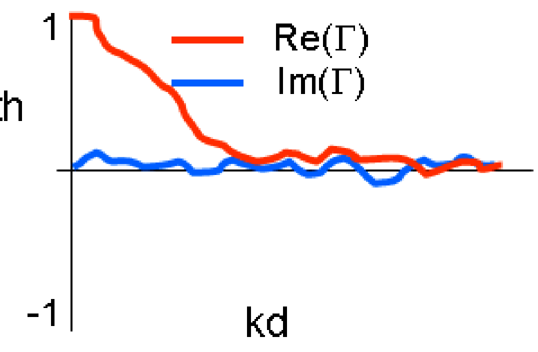
SCALED RANGE

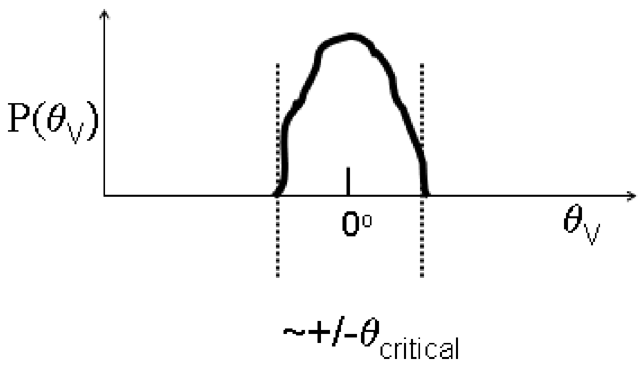
Range/Depth < 10





Range/Depth > 10





Summary

- Spatial coherence subject to significant bias, particularly at $|\Gamma| < \sim 0.2$

- Rough surface PE simulations compare well with observations (comparison only for ranges < 1 km)

- For short ranges (Range/Depth < 10) multipath $|\Gamma|$ is highly oscillatory, (ray view point)

- For long ranges (Range/Depth) > 10 multipath $|\Gamma|$ becomes monotonic

- Spatial coherence increases with range due to mode stripping:
  - short range: sea surface plays a strong role (modeled in this work)
  - longer range: ocean dynamical effects will dominate (*not* modeled in this work)

- Increasing spatial coherence with range has important implications in terms of modeling reverberation and signal processing gain