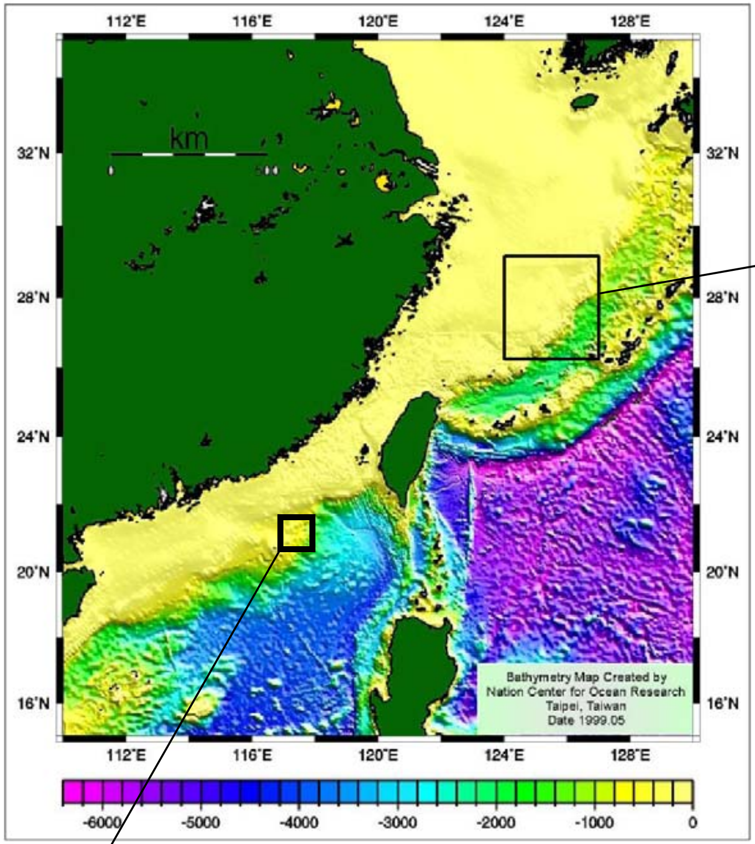
SHALLOW WATER ACOUSTICS
….GRAND CHALLENGES….

Ira Dyer, MIT, 14 June 2007

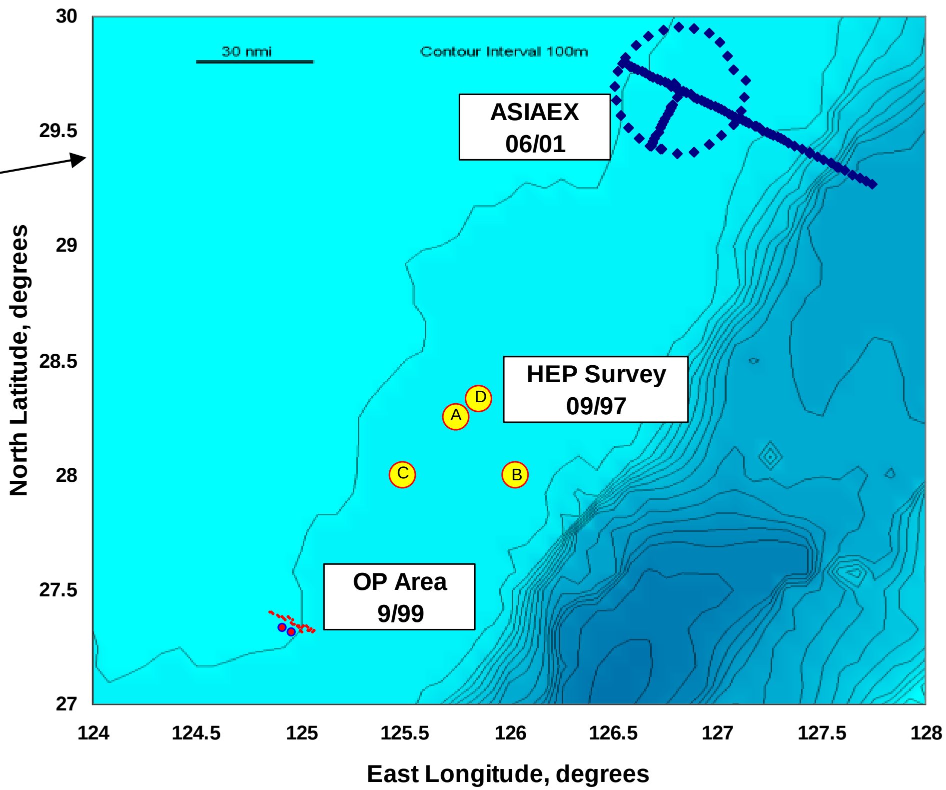
My talk is borrowed in spirit from David Hilbert who, at age 38 in 1900, defined 23 mathematical challenges that more than a century later, while all not fully resolved, shaped the course of advances in that field from then until now.

He gave grand definitions. Instead, I point to challenges that address the present crisis in satisfactory understanding and prediction of acoustics in shallow water environments.

TRANSMISSION DATA IN SHALLOW CHINA SEAS



East China Sea (ECS) Test Sites

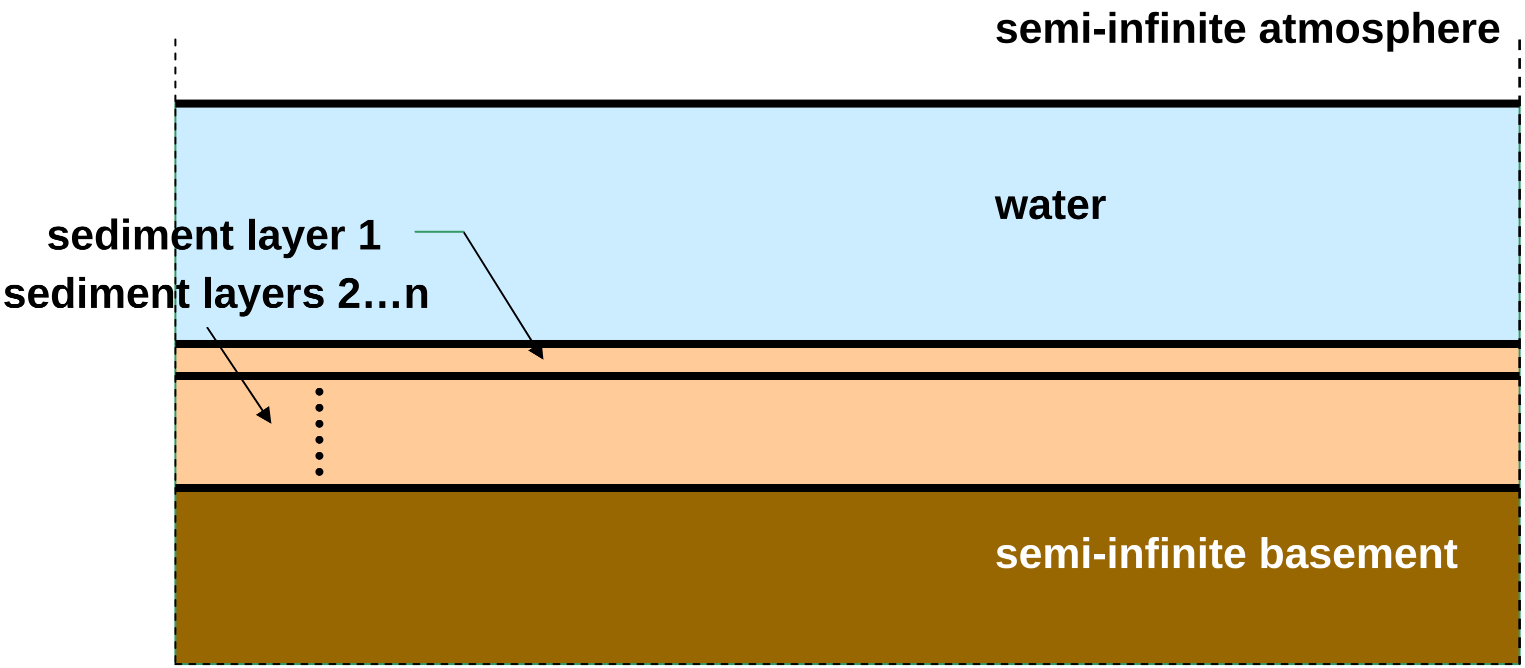


South China Sea (SCS) Tests

My paper will mainly use test results in shelf waters that are about 100 m deep

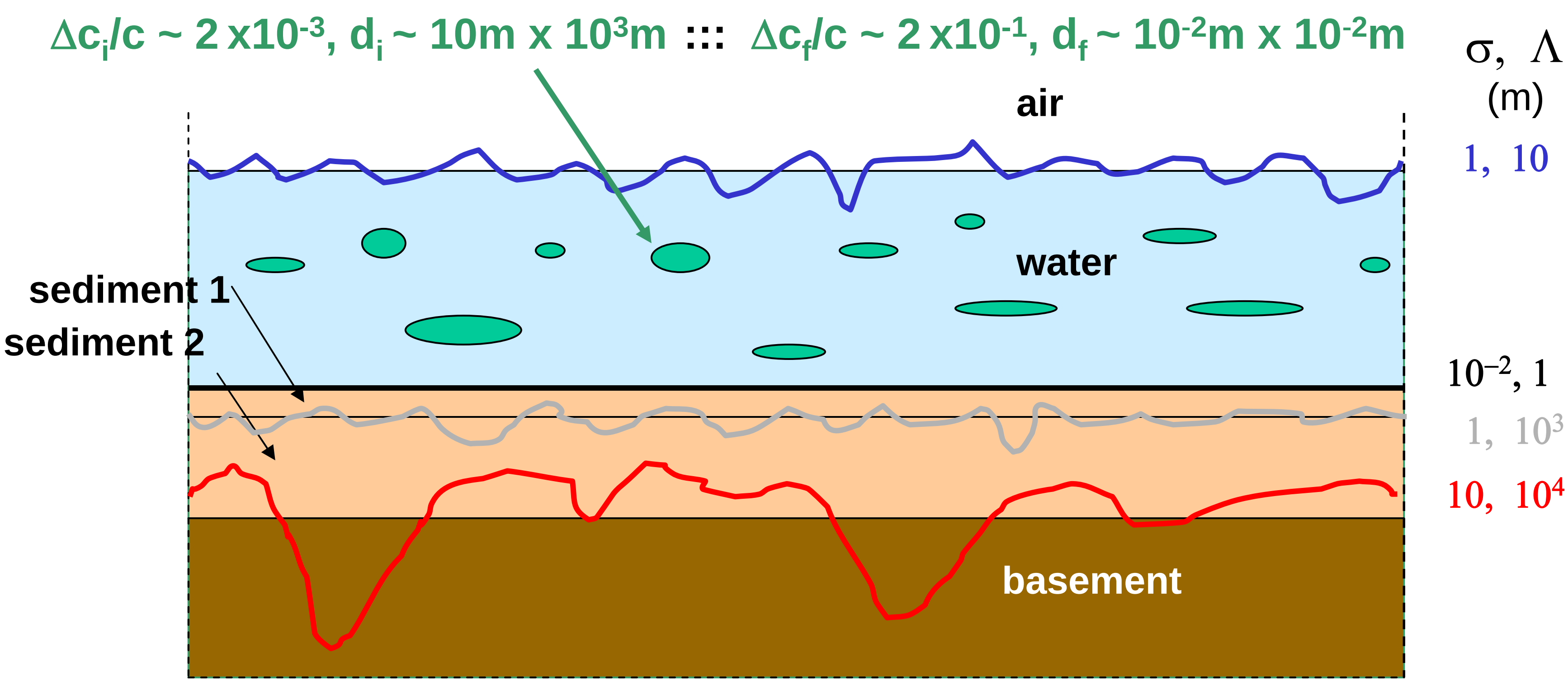
THE CANONICAL MODEL OF THE ACOUSTICS DUCT FOR SHELF WATERS

The two-dimensional plane shown idealizes the cylindrical volume containing the sound



For slowly-varying depth- and range-dependent values of the material properties of the layers, acoustic transmission in a shelf duct can be readily calculated. **Despite the stark simplicity of the canonical model, it is surprisingly informative.** Later caveats, however, underlie the challenges to fuller understanding of shallow water (SW) acoustics on the shelf.

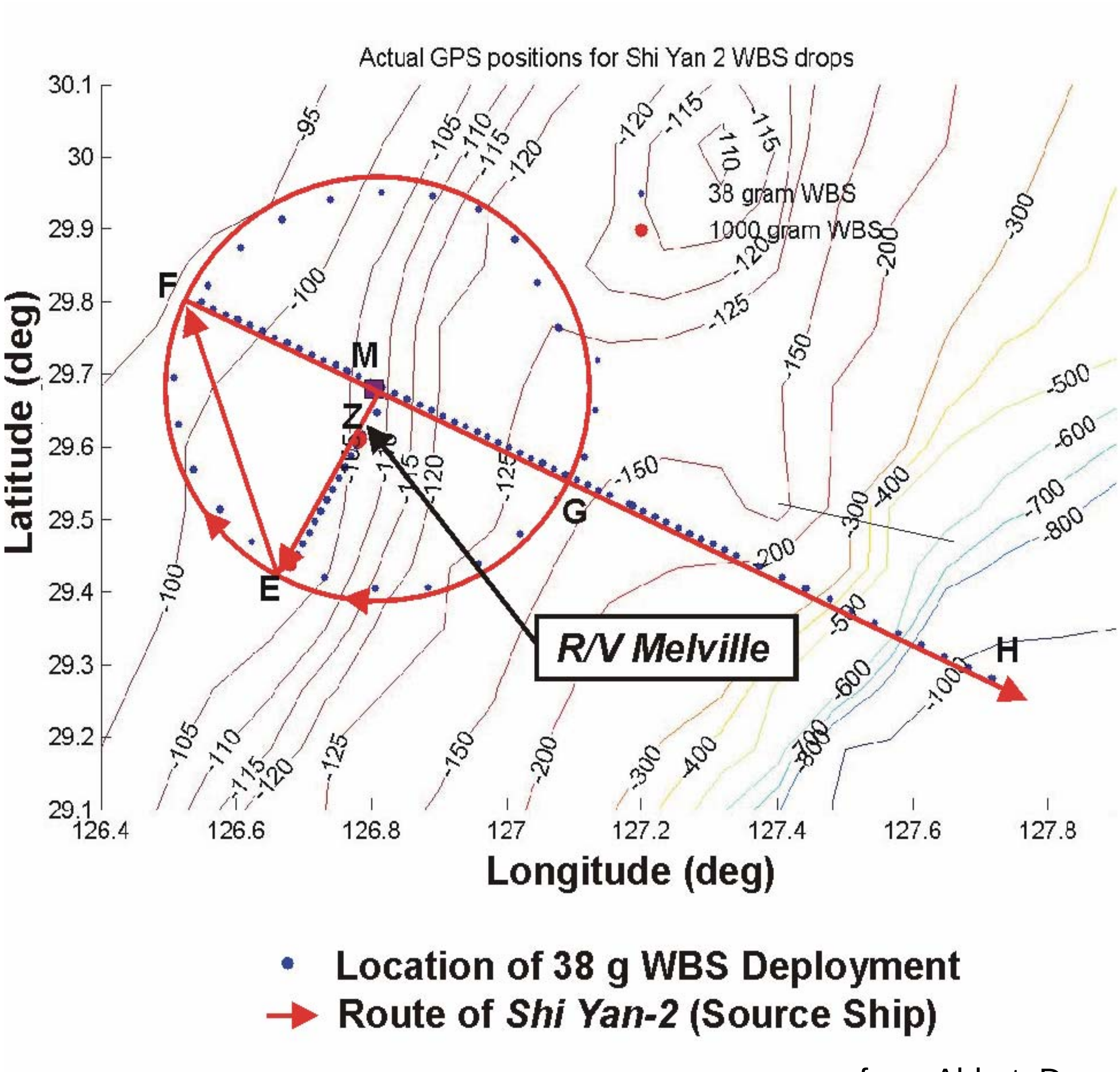
THE REAL ACOUSTICS DUCT FOR SHELF WATERS HAS DEFECTS



Height & length scales (σ,Λ) of the duct's interfaces, and sound speed-contrasts & length scales (Δc,d) of the volume inhomogenieties lead to **scattering** and to **spatial decoherence** of the signal and noise. Duct defects can affect the mean values of transmission and noise *via* **net out-of-plane scattering losses**. Also, the defects, and motions of the source, of the receiver, of the air/water interface, and of the water inclusions contribute to **temporal decoherence**.

ECS ASIAEX 3 June 2001

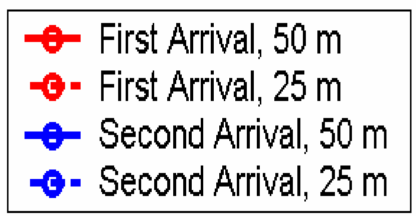
Systematic Transmission Data *vs* Bearing: A Breakthrough in Test Design



from Abbot, Dyer, & Emerson, 2006

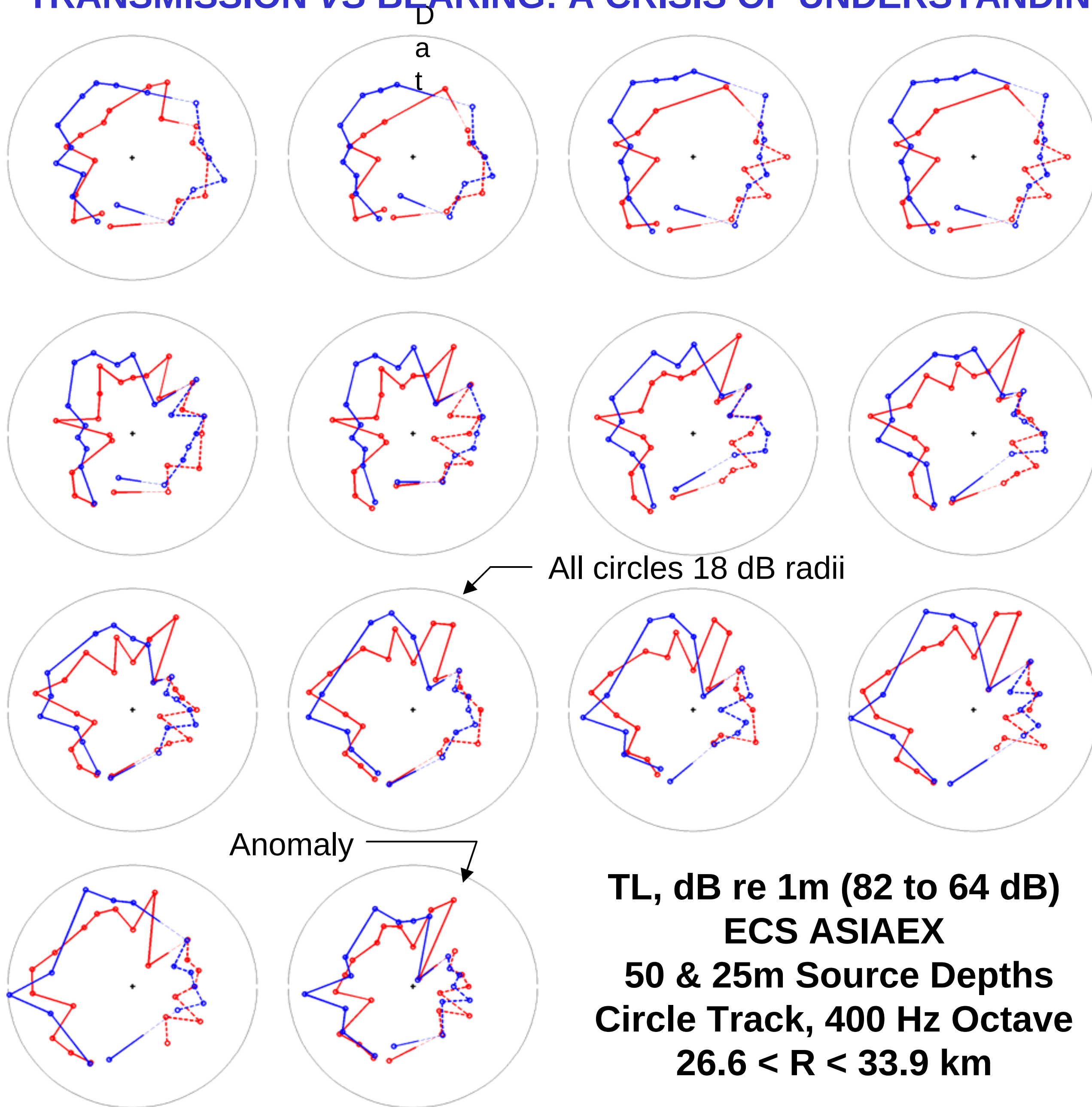
TRANSMISSION *VS* BEARING: A CRISIS OF UNDERSTANDING

Measured Transmission
from Circle to Center,
First arrives10 s
before the **Second**



The polar plots are vs source bearing β, for normalized receiver depths in the usual reading order: d/D = 0.33 to 0.82 in 14 equal increments

Caution: some data are missing



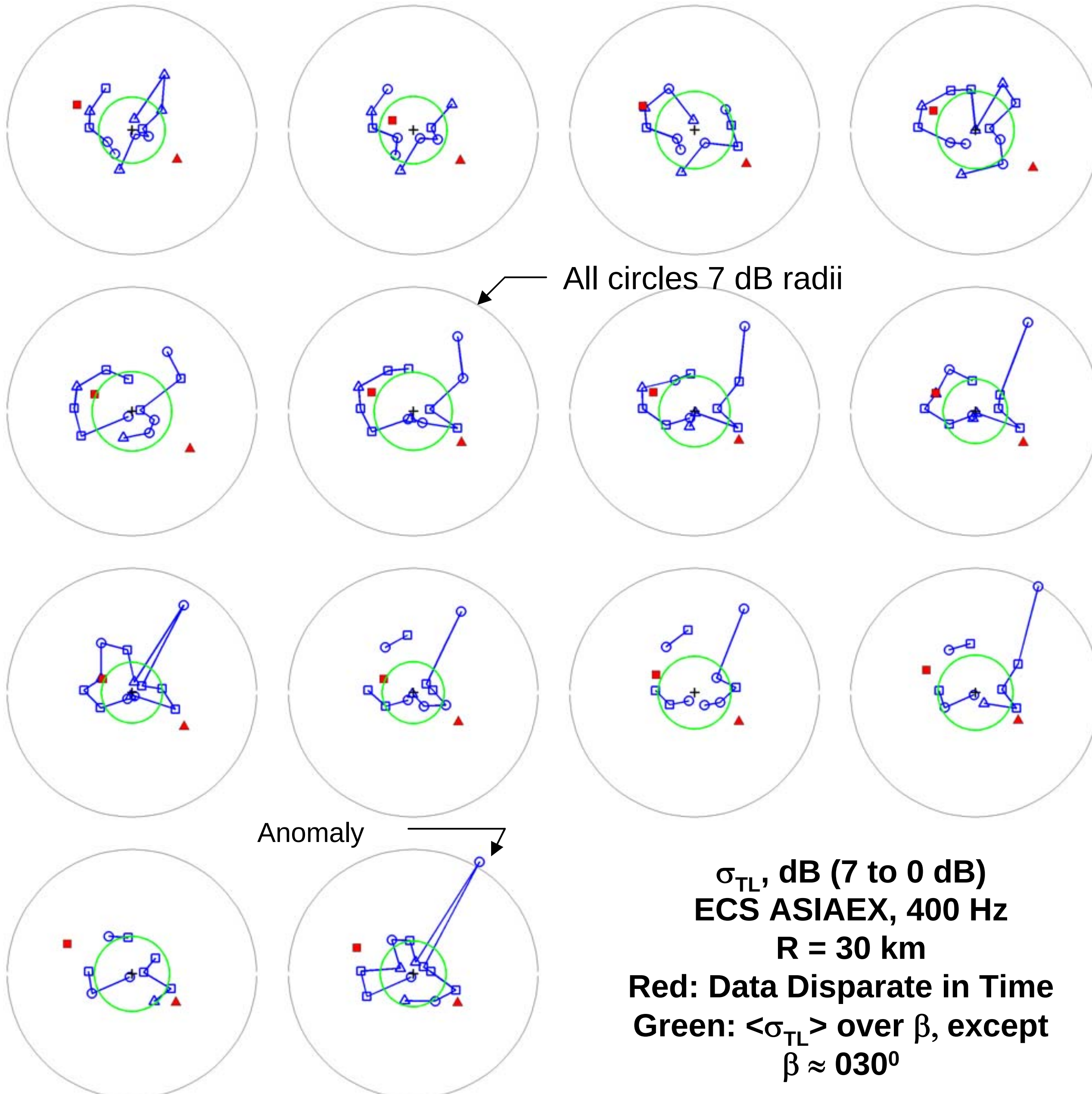
TL, dB re 1m (82 to 64 dB)
ECS ASIAEX
50 & 25m Source Depths
Circle Track, 400 Hz Octave
26.6 < R < 33.9 km

from Abbot, Dyer, & Emerson, 2006

Standard Deviation σ_{TL} from Smoothed & Assimilated Transmission

4 point set
3 point set
2 point set

With the anomaly at $\beta \approx 030^0$ excluded, the σ_{TL} is approximately independent of β (*i. e.*, isotropic), and of value: $\sigma_{TL} \approx 2$ dB (green circles)



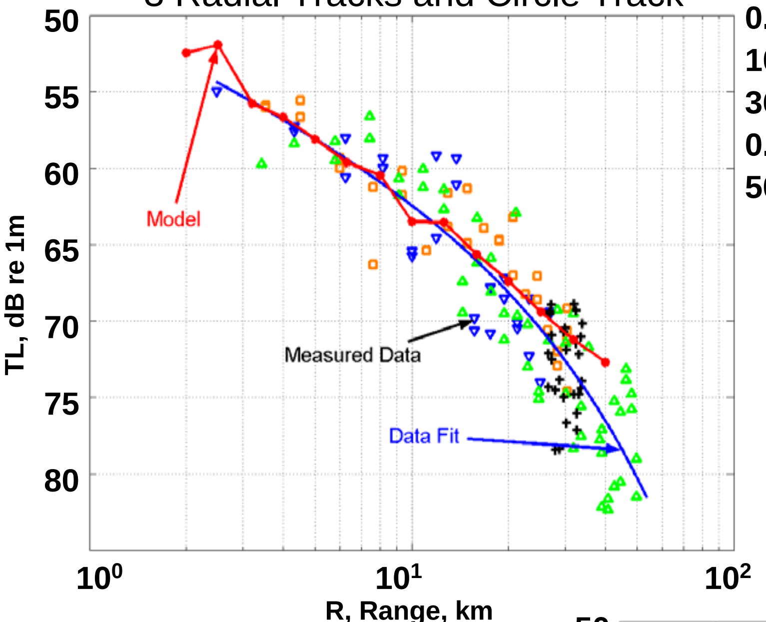
σ_{TL}, dB (7 to 0 dB)
ECS ASIAEX, 400 Hz
R = 30 km
Red: Data Disparate in Time
Green: $\langle\sigma_{TL}\rangle$ over β, except $\beta \approx 030^0$

from Abbot, Dyer, & Emerson.2006

ECS Transmission Measurements, 400 Hz, Octave Band, $d_S = d_R$,

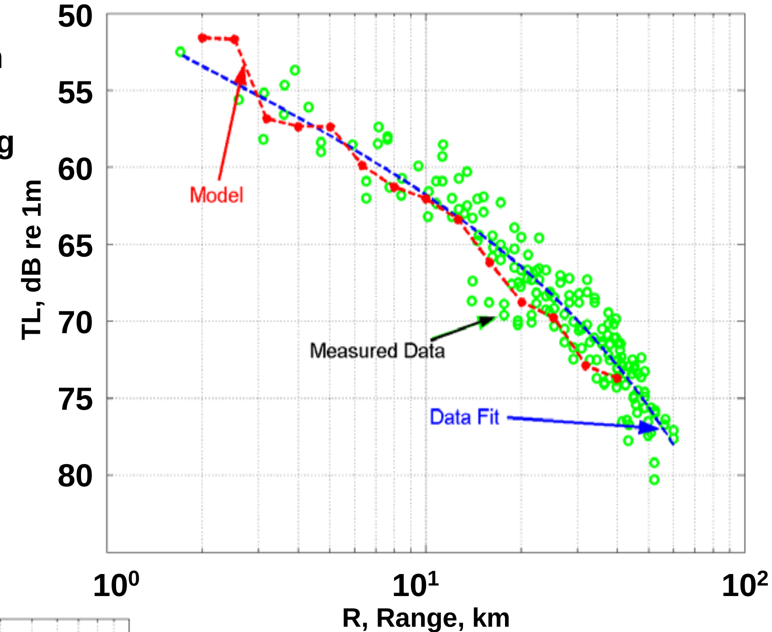
Smoothed Data Fits and RAM Canonical Model Calculations

ASIAEX (June 2001)
3 Radial Tracks and Circle Track

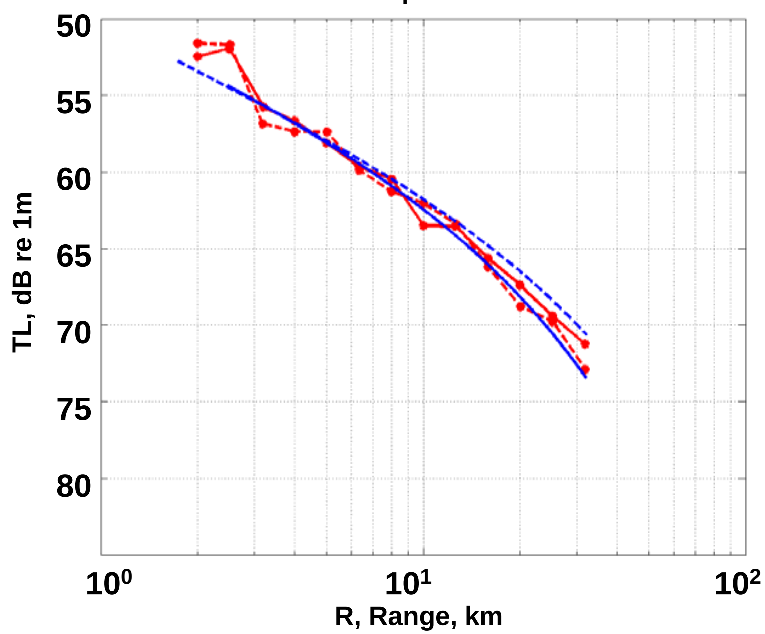


0.48	d/D	0.18
105 m	D	100 m
36	T B	180
0.038 kg	S. Wt.	0.82 kg
50 m	S. Depth	18 m

HEP (Sept. 1997), 4 Radial Tracks



Comparisons



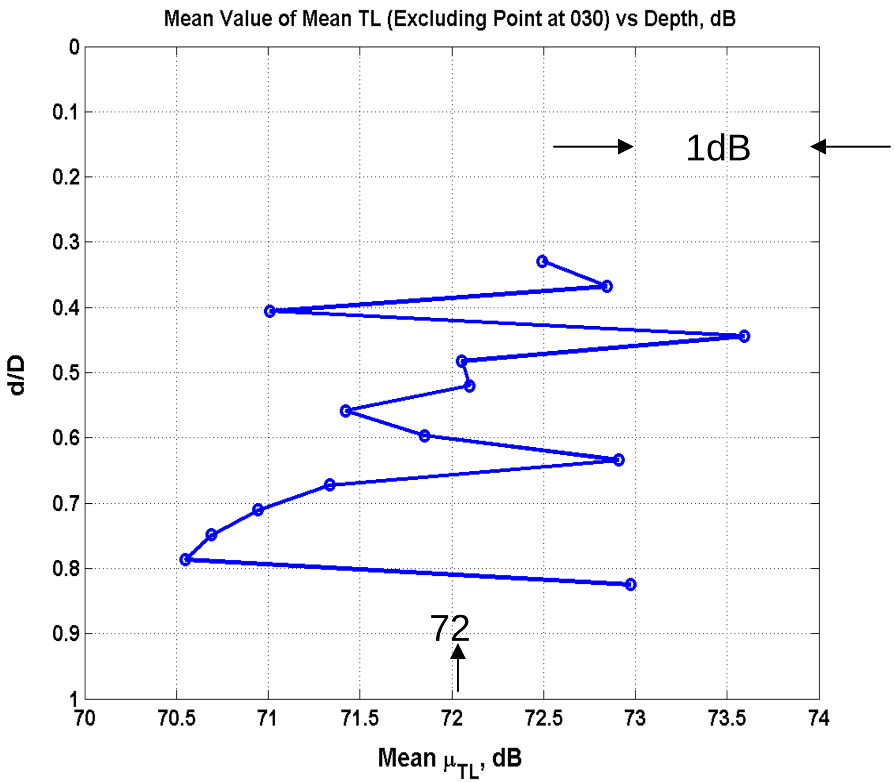
With exclusion of the anomaly, and from data in range-bins, we obtained $<\mu_{TL}>_\beta$, the bearing-averaged transmission mean *vs* range.

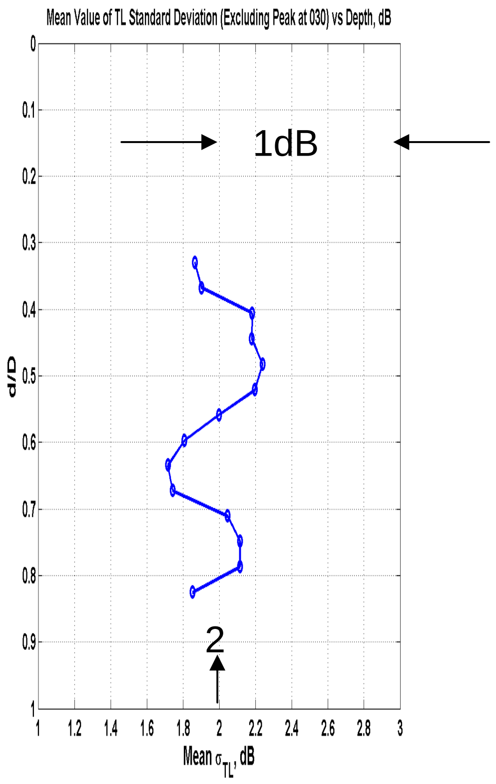
The canonical model can robustly predict $<\mu_{TL}>_\beta$, defects not withstanding!

from Abbot, Dyer, & Emerson, 2006

Mean ($<\mu_{TL}>_\beta$ on left) and Standard Deviation ($<\sigma_{TL}>_\beta$ on right) Measured vs Normalized Depth, ECS, ASIAEX 2001

400 Hz Octave, $000^0 \leq \beta \leq 360^0$ excluding the Anomaly at $\beta \approx 030^0$
Assimilated to R = 30 km and d_s = 50m





from Abbot, Dyer, & Emerson 2006

ASSERTIONS/CHALLENGES IN SW ACOUSTICS I

Assertion: While transmission data show μ_{TL} *to be dependent on* source/*receiver bearing* β *on the shelf (see Slide 6), the canonical duct can be used to predict, as supported by Slide 8, sound transmission for shelf waters averaged over bearing* ($<\mu_{TL}>_\beta$)*. Some, but not all, of the crisis in understanding is thus overcome.*

Challenge 1: What are the physical limits of this assertion in relation to the observable properties of the ocean? As examples:

- Does this assertion hold for all combinations of duct defects?
- Do transmission data for all broad shelf waters behave similarly?
- Do shelf currents, or eddies shed from major continent-hugging circulations such as the Gulf Stream, play a role?
- Because they can cause out-of-plane losses, are rough sea surfaces or fish schools, truly negligible in determining the mean $<\mu_{TL}>_\beta$?

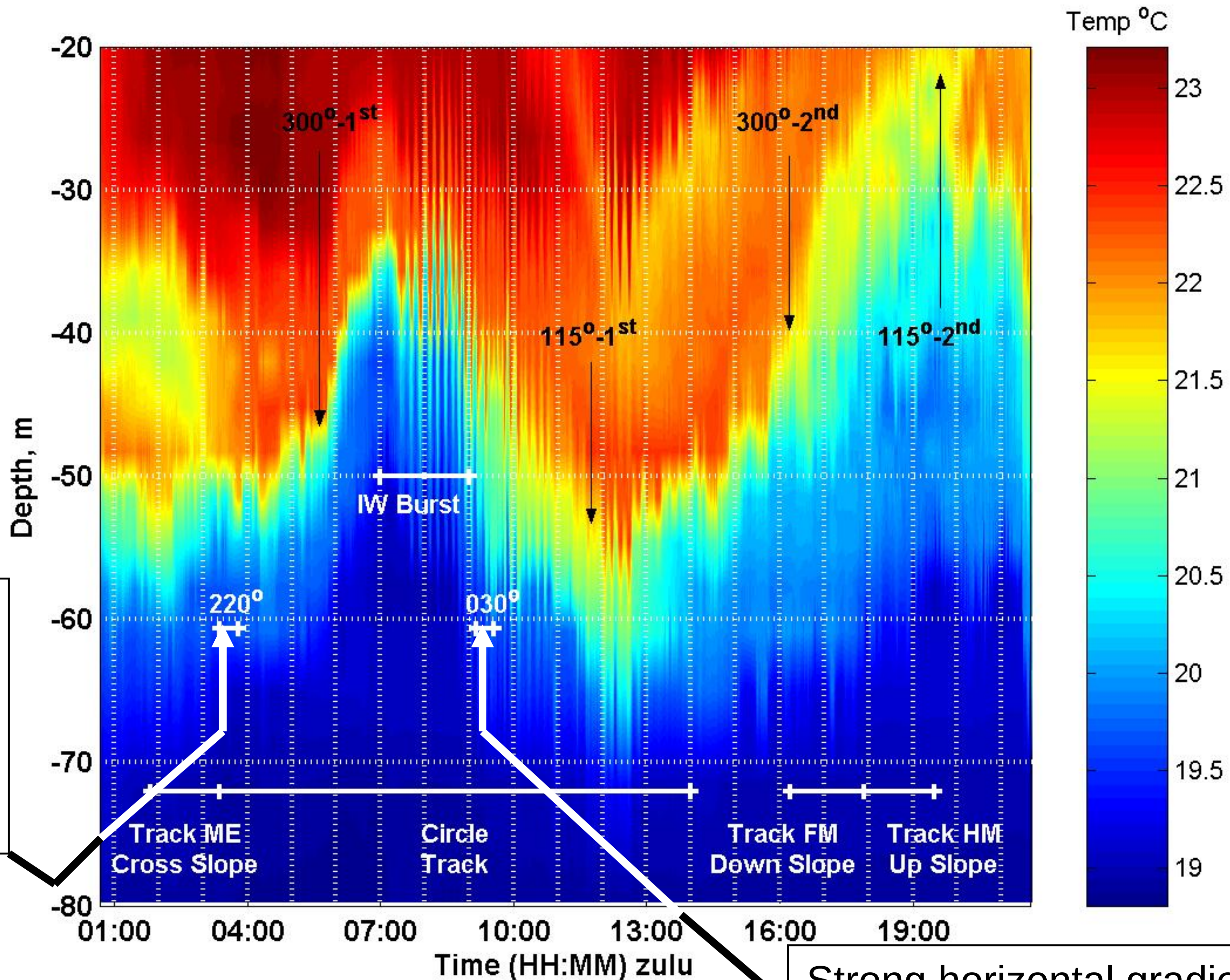
CONSIDERING OCEAN ENVIRONMENTAL DEFECTS

Assertion: Understanding and predicting the mean ($<\mu_{TL}>_{\beta}$) is conceptually easy via the canonical model. But the absence of defects in this model has the effect that it cannot correctly predict other highly-desired properties of the sound field, including fluctuations around the mean (e.g.,σ_{TL}), scattering (e.g., reverberation), scattering-induced losses, and spatial and temporal decoherence.

We consider next some defects, as revealed by SW experiments. These couple acoustics to data from two ocean environmental disciplines (physical oceanography and ocean geology/geophysics), but this is enough to illustrate the quest for better and fuller understanding.

The Internal Tide: An In-Water Macroscale Defect Well Resolved by Thermistor Data

ECS ASIAEX, 3 June 2001, at Station M, 20 sensor Chain, *Shi Yan-3,* (Peng *et al*)



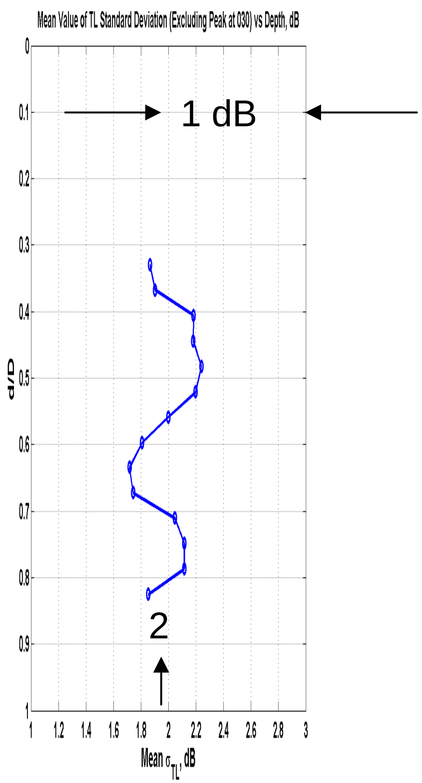
In overall this is a "macroscale" defect; the major features are > 100 km in length.

Weak g_H: refracts mostly in-plane; no anomaly

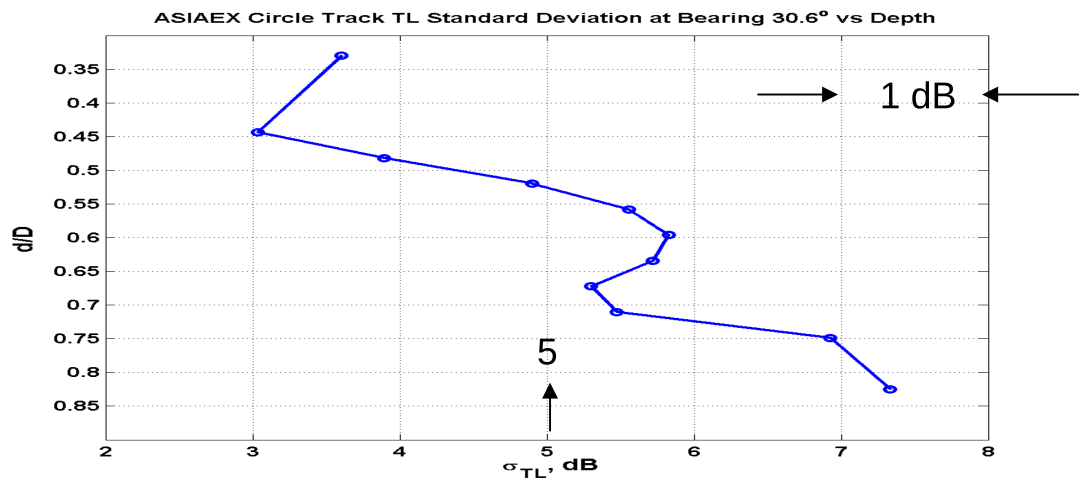
Strong horizontal gradient (g_H): sound refracts in & out-of-plane, and explains the anomaly at $\beta \approx 030^0$

Standard Deviation (σ_{TL}) vs Normalized Depth Excluding (left) and Only for the Anomaly at $\beta \approx 030^0$ (right)

ECS ASIAEX 2001, 400 Hz Octave, R = 30 km



The macroscale anomaly is spatially and temporally rare (Finette, 2003) but, when observed, has a large standard deviation sharply dependent on depth

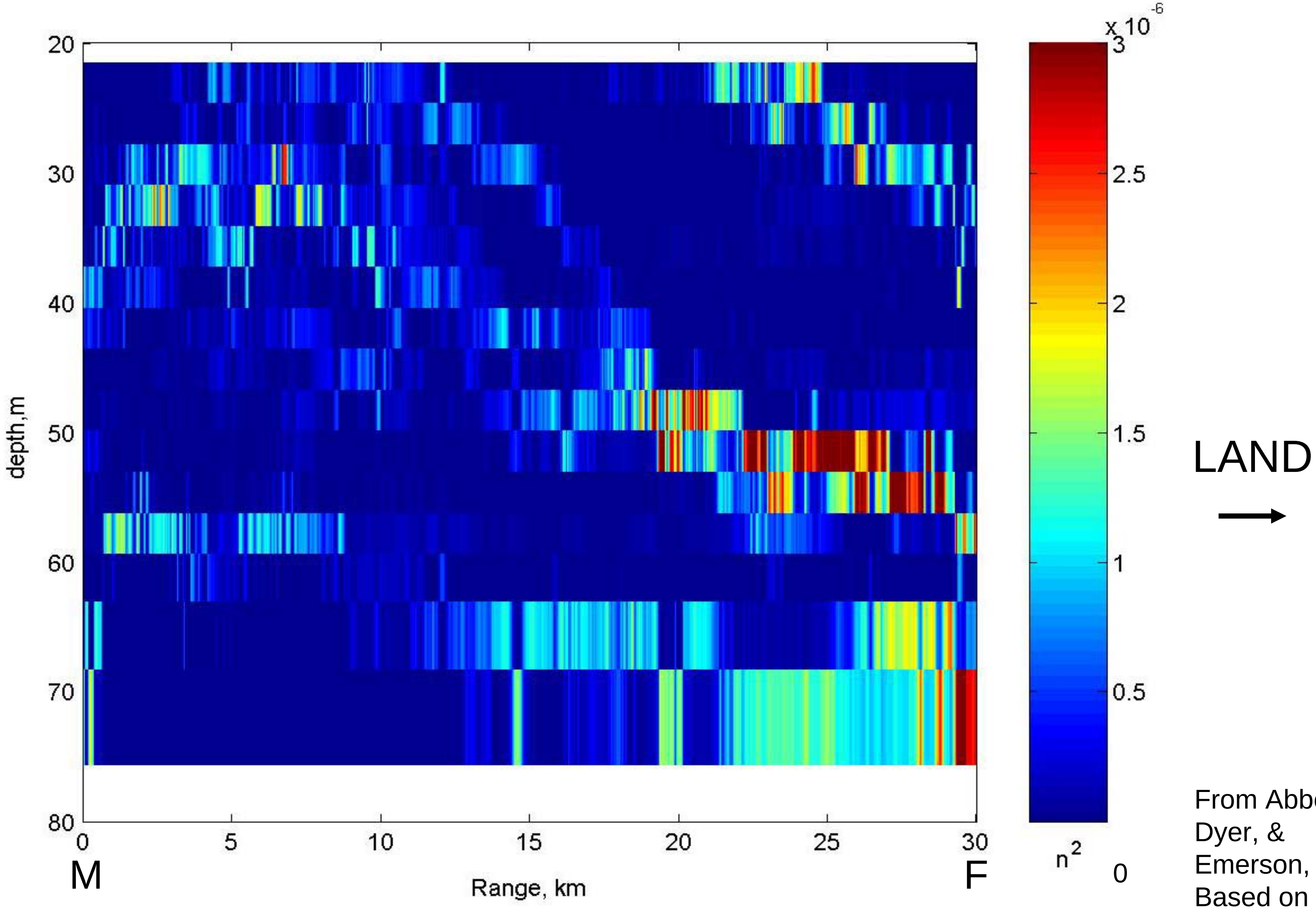


from Abbot, Dyer, & Emerson, 2006

Microscale Contrast Volumes, n^2 *vs* R and d, are Numerous but Weak, and Poorly Resolved by Thermistor Data

Vertically Quantized, Rigid Advection Landward (assumed at 0.9 m/s)
Oppositely Directed Acoustic Propagation Wavevector (at ≈ 1500 m/s)

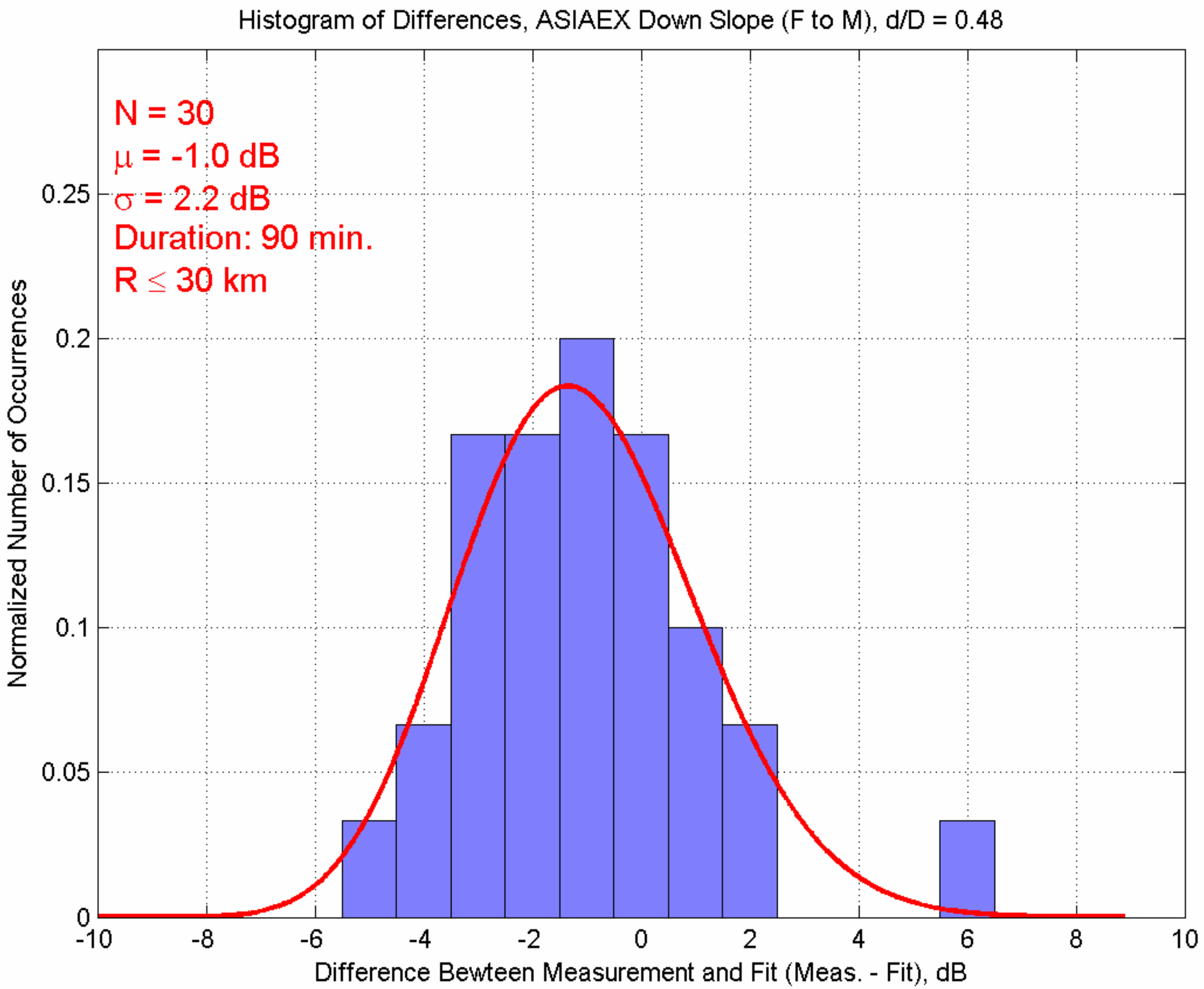
$n^2 = (\Delta c/c)^2$



From Abbot, Dyer, & Emerson, 2006. Based on Peng *et al*

Histogram of TL, Radial Track (F/M), $\beta = 300^0$

ECS ASIAEX, $d_R = d_S = 50$ m

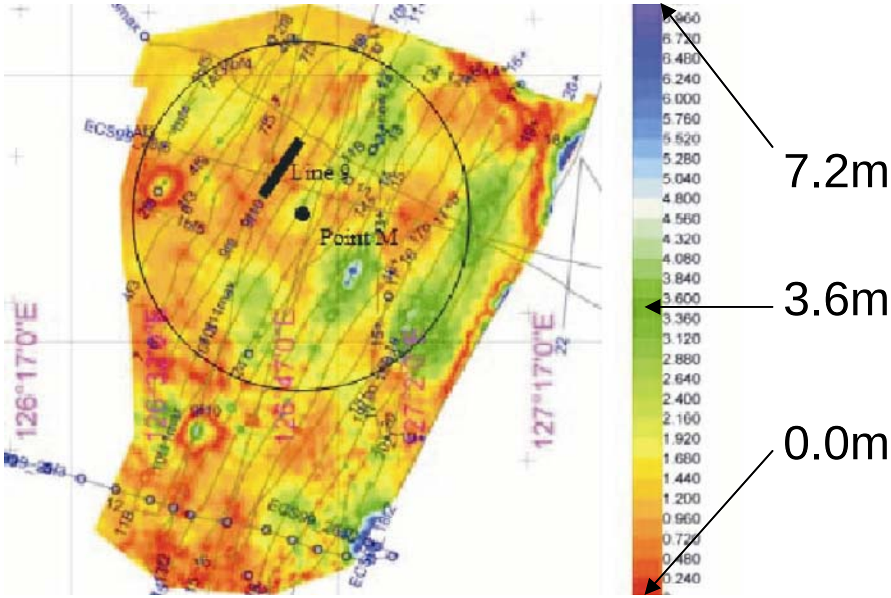


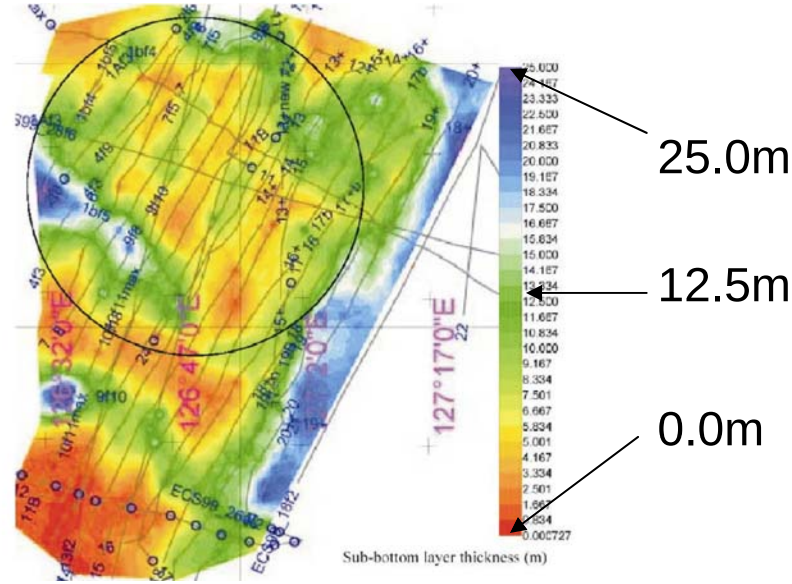
Comments on Acoustics and Physical Oceanography

Delineation of 2D <u>macroscale</u> features from temperature data *vs* depth and time, as in standard physical oceanography, provides only part of the fundamental information needed to understand real duct acoustics. Also, there are limitations to this standard:

- **A <u>macroscale</u> temperature slice as shown in Slide 12, being 2D, can answer questions only partially on the 3D acoustic field**
- **But the temperature field can be measured in 3D with use of mobile sensors and assimilative modeling; this recently has been shown to be feasible (Gawarkiewicz, 2007), and hopefully will become standard**
- **3D <u>microscale</u> features from temperature data, however, are not measured at all or, if so, are too poorly resolved for acoustic analyses**
- **Other water-dynamical defects, such as the rough sea surface or dense fish schools, each a defect class with strong acoustic contrast (Makris *et al,* 2006), are typically not measured simultaneously with acoustic tests**

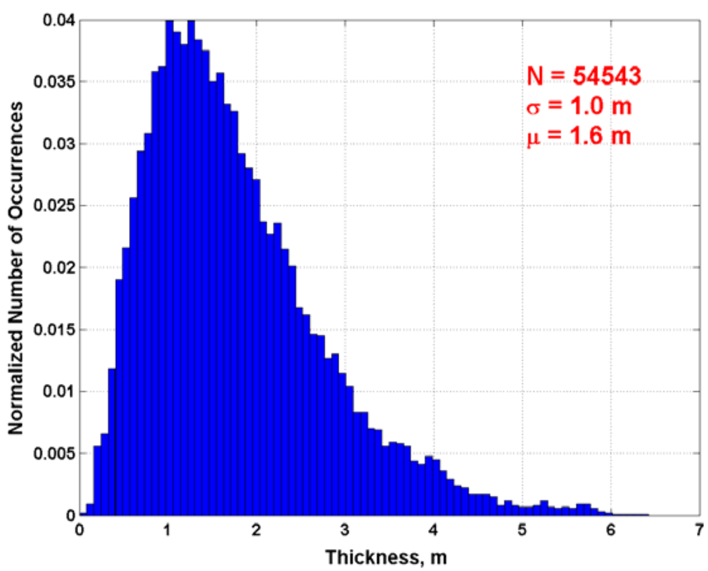
Thickness of the two ASIAEX Sedimentary Layers

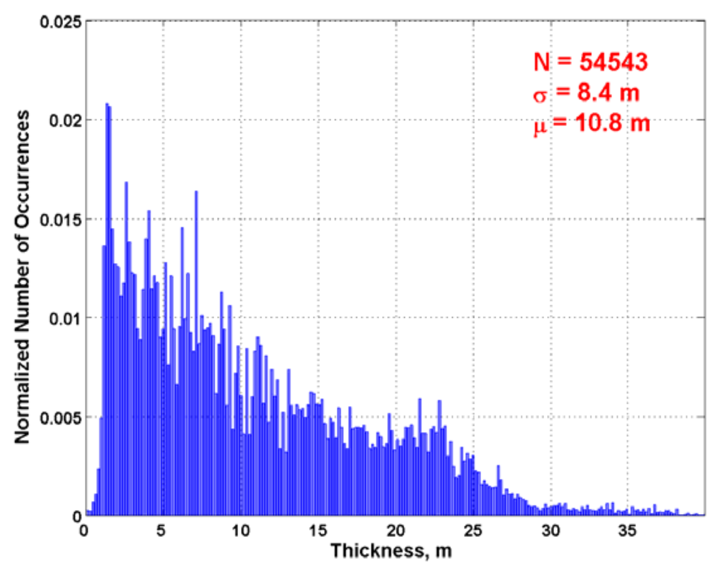




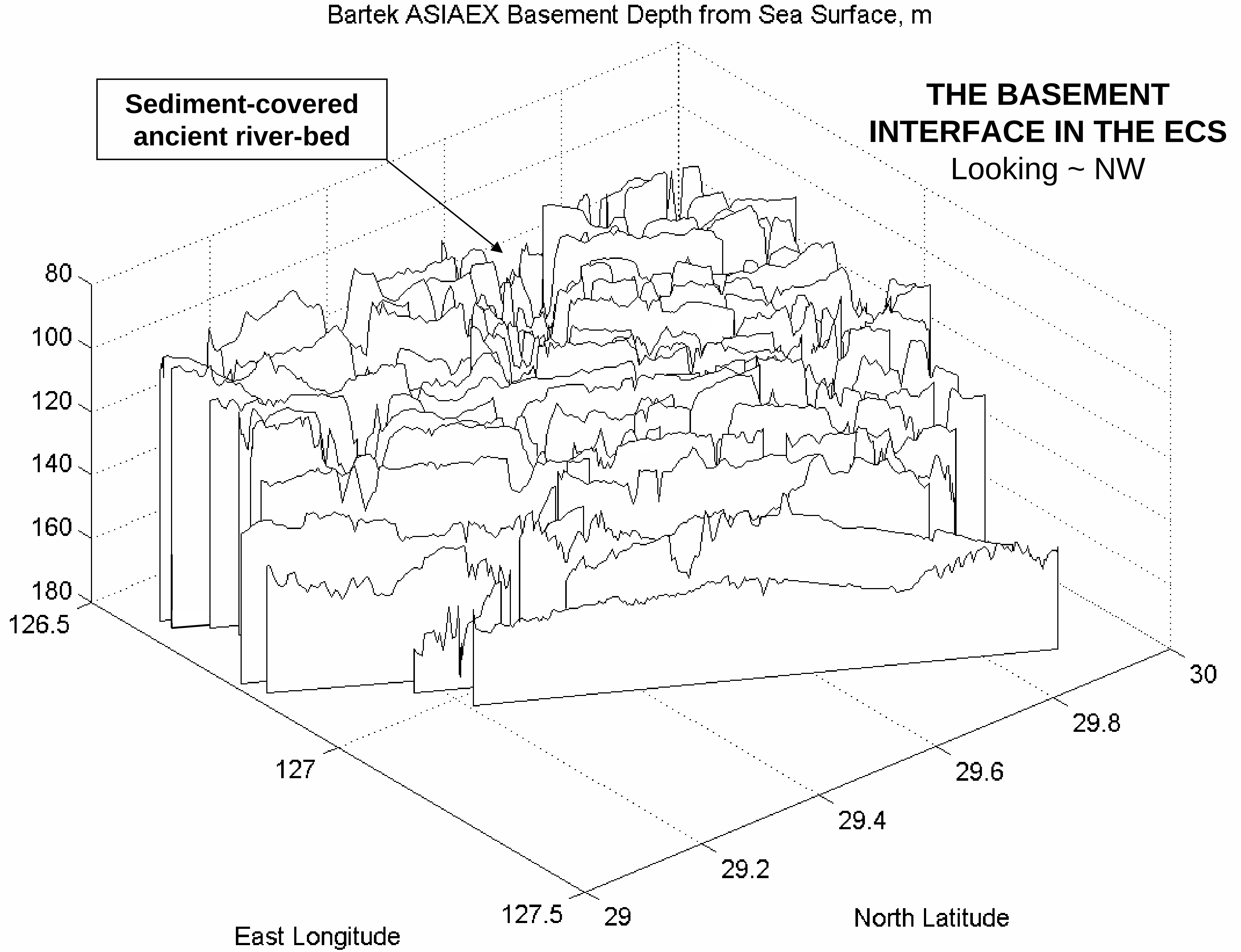
First Layer. Between water and second layer, μ = 1.6 m

Second Layer. Between first layer and basement, μ = 10.8 m

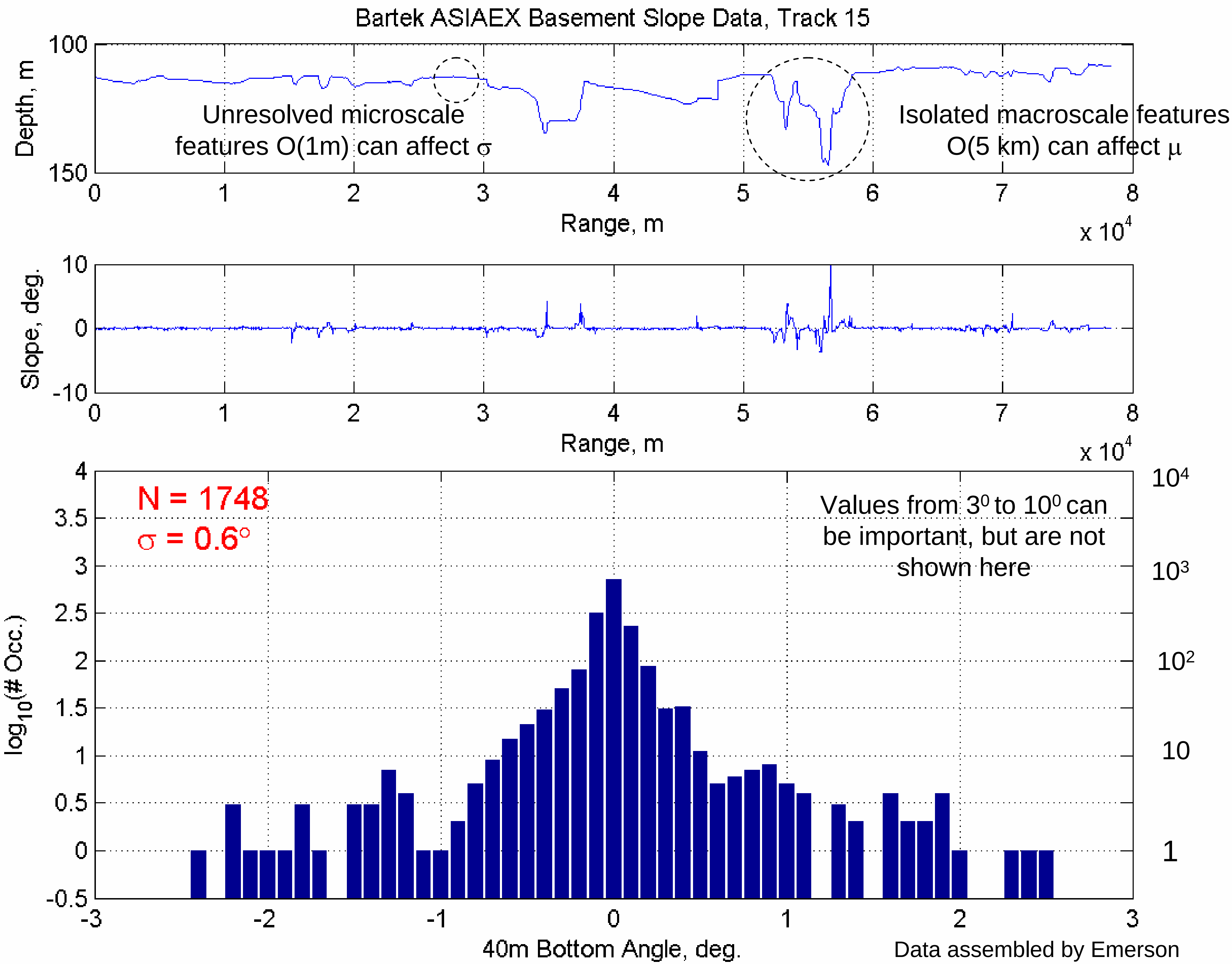




from Bartek data

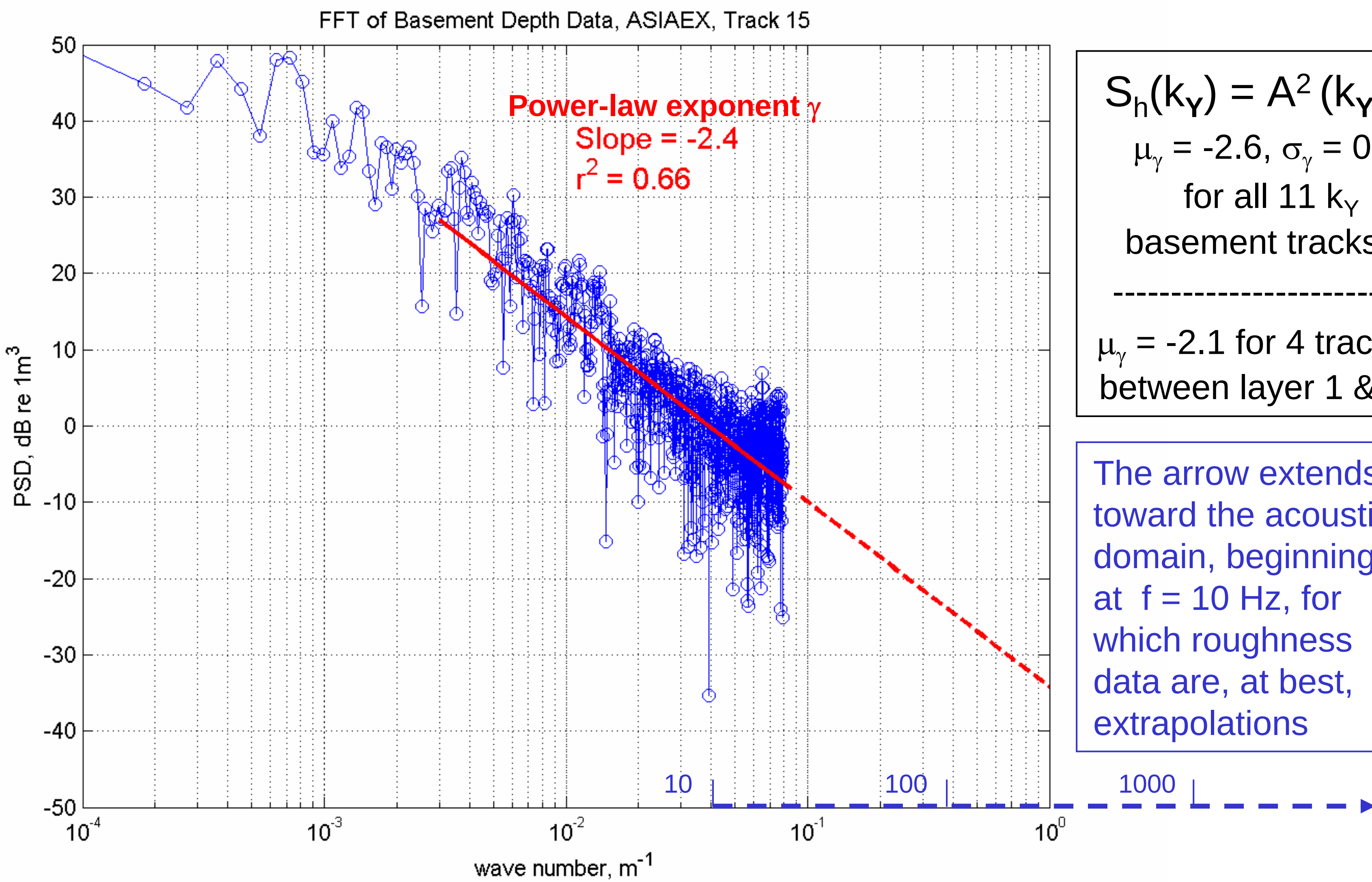


Data assembled by Emerson & Dyer


Bartek ASIAEX Basement Slope Data, Track 15
Depth, m
Unresolved microscale
features O(1m) can affect σ
Isolated macroscale features
O(5 km) can affect μ
Range, m
x 10^4
Slope, deg.
Range, m
x 10^4
log10(# Occ.)
N = 1748
σ = 0.6°
Values from 3⁰ to 10⁰ can
be important, but are not
shown here
40m Bottom Angle, deg.
Data assembled by Emerson

One-Dimensional Wavenumber Spectrum $S_h(k_Y)$ of Basement Depth

(Depth Track 15, ECS Data)



k_Y

$S_h(k_Y) = A^2 (k_Y)^{-\gamma}$

$\mu_\gamma = -2.6$, $\sigma_\gamma = 0.4$ for all 11 k_Y basement tracks

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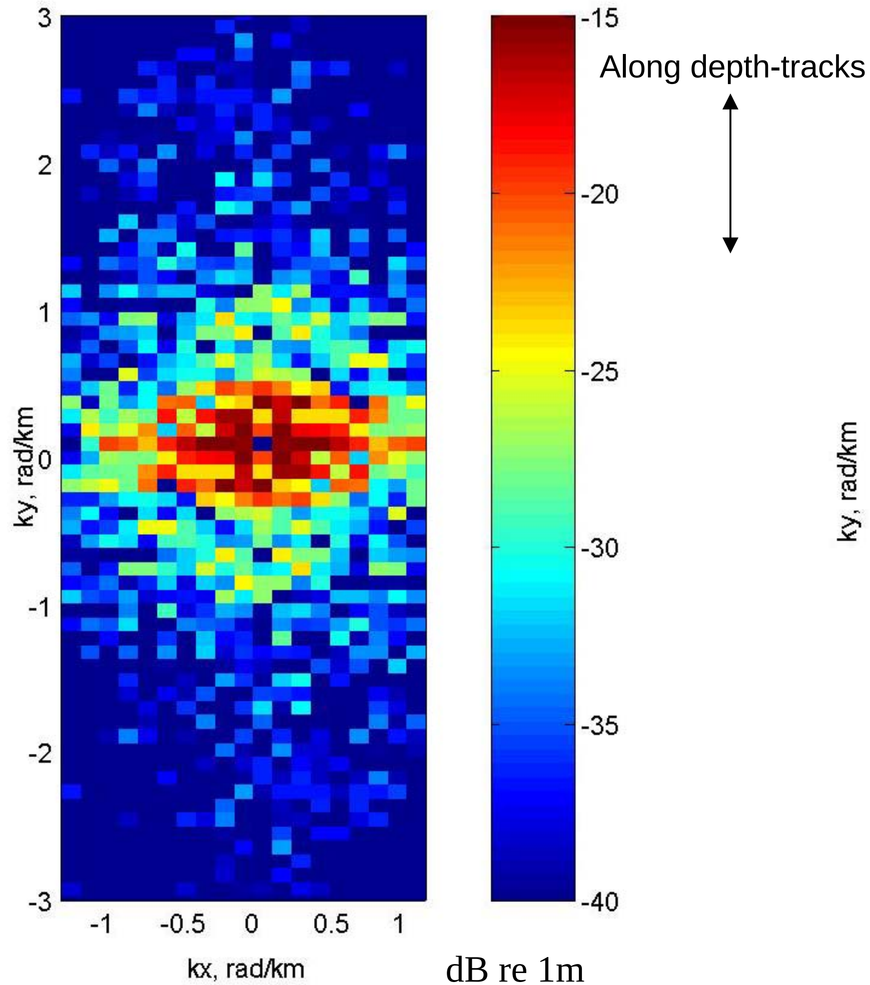
$\mu_\gamma = -2.1$ for 4 tracks between layer 1 & 2

The arrow extends toward the acoustic domain, beginning at f = 10 Hz, for which roughness data are, at best, extrapolations

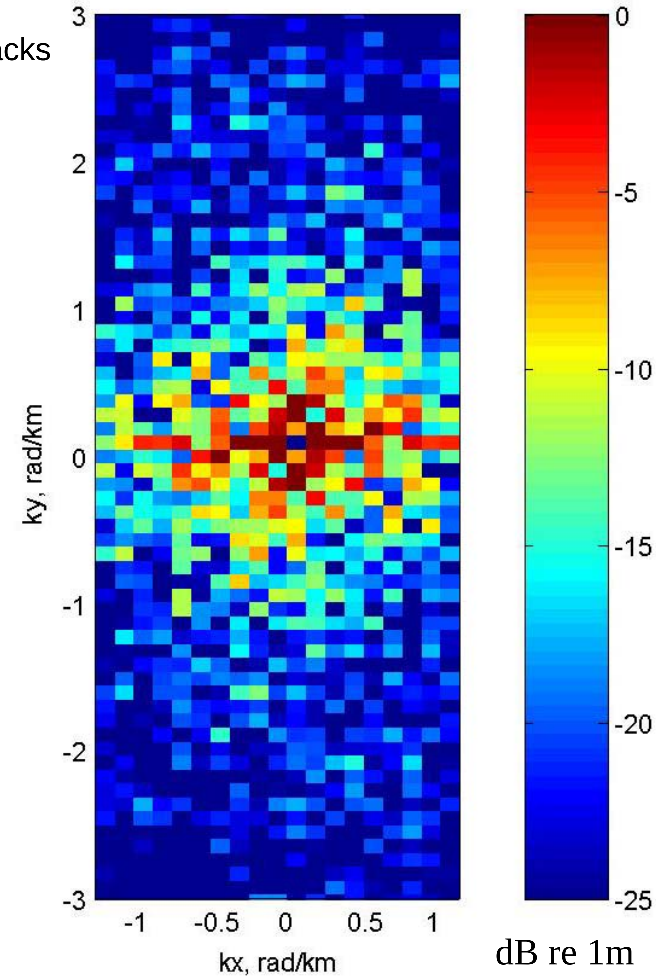
Analysis by Emerson of Bartek's data

2D Wavenumber Spectra of the two ASIAEX Bottom Interface Depths* Appear Approximately Horizontally Isotropic, with O(10) Larger Spectral Density for the Basement Interface

Between layer 1 and 2



Between layer 2 and basement



Abbot, Dyer, & Emerson, 2006

from Bartek data

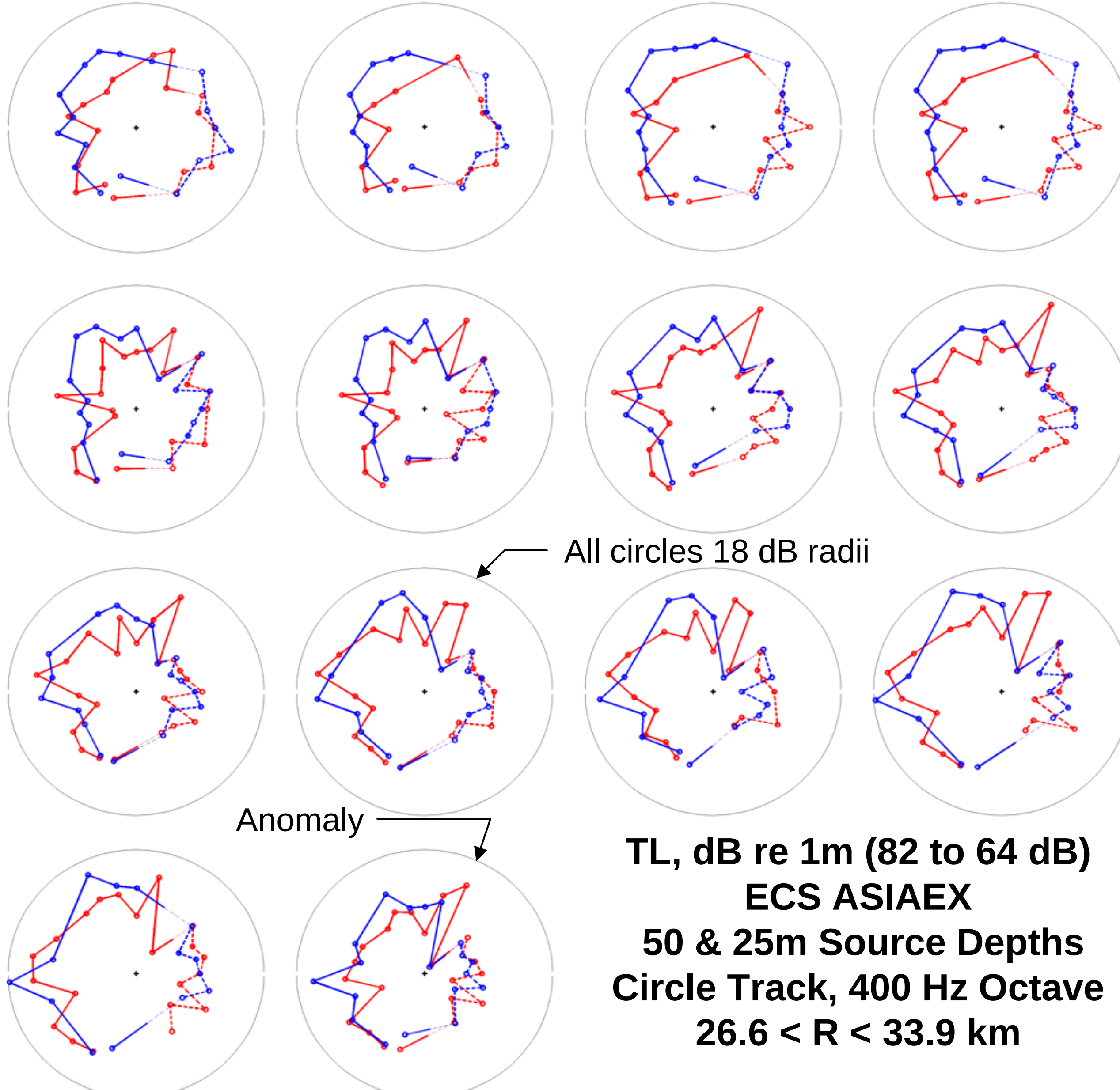
* Inferred from Sediment Layer Thickness

Acoustics and Ocean Geology/Geophysics

- Pseudo-3D shelf-bottom features, from standard ocean geology/geophysics, also pertain to real duct acoustics. Although the sediment-covered ancient river-bed is a lineal feature, the measured 2D macroscale roughness appears to be more isotropic than anisotropic.
- Two rough interfaces were delineated in the ECS shelf bottom, the first of O(1 m) into the bottom, and the second at the basement of O(10 m) deeper. The first is probably not rough enough to significantly disrupt evanescent waves in the bottom (and thus not affect low-angle bottom acoustic reflectivity), and the second carries macroscale scars from its tectonic and erosive history that could scatter sound strongly, but mainly for angles larger than critical (Abbot, Dyer, & Emerson, 2006).
- Roughness spectra, and the derived roughness slopes, show that <u>macroscale flat sections</u> are numerous, more so for the interface between layer 1 and 2, than for the basement. Also, while basement microscale features at the high wavenumbers pertaining to the acoustic domain can be extrapolated from low wavenumber data, this comes with uncomfortable risk.

Could Macroscale Defect Length-Scales Λ_1 (mean distance between neighboring defects) and Λ_2 (mean size of defects) be Estimated from these Data?

Measured Transmission
(Data Shown Earlier)



The two arrivals, 10 s apart, are poorly correlated, more so in NW sectors. At R = 30 km, one could dismiss the sediment-covered ancient river-bed as an important scatterer (but not for R < 10 km).

Caution: some data are missing

TL, dB re 1m (82 to 64 dB)
ECS ASIAEX
50 & 25m Source Depths
Circle Track, 400 Hz Octave
26.6 < R < 33.9 km

Fluctuation Statistics and Inferred Defect Scales

- The 10 s interval between the First and Second transmission samples at each β in the ECS circle is too large to define a temporal scale. Rather, in this interval, the source translated $\approx$ 51 m or about 14 acoustic wavelengths. This is more than enough to invoke phase-random (pr) statistics for the β sample-set that includes the 1st and 2nd arrivals, resulting in $\sigma_{pr} \approx 0.2$ dB; this decreases the observed σ_{TL}, a difference in this case of O(0.01) dB that is small enough to be ignored.
- The distance between the inferred defect peaks might suggest $\Lambda_1 \approx$ O(15 km), and the width of the peaks $\Lambda_2 \approx$ O(4 km)*. Either or both of these might be plausibly connected to macroscale defects caused by the internal tide, or by the bottom, or by other defect classes. The correlation between the 1st and 2nd arrivals is acceptable for an average of only 3/25 of the 14^0 bearing sectors; it is thus inappropriate to accept these scale inferences.

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*The bearing interval $\Delta\beta \approx 14^0$ at R = 30 km has a circumferential period $\approx$ 7.3 km, so that scales shorter than this cannot be resolved. That is, much finer sampling in β is needed.

OASIS Mobile Acoustic Source (OMAS)

OMAS Characteristics

Precision Clock

Calibrated Sound Source

Specialized Acoustic Transmissions

LBL Tracking Systems

Field Applications

SCORE Range 04

South China Sea 05, ECS 06

New Jersey Experiments 05, 06

Standard EMATT (LM Sippican)

Length: **91.4 cm (36")**

Diameter**: 12.4 cm (4.9")**

Weight**: 10 kg (22 lbs)**

Battery Power**: LiSO4**

Operational Characteristics

Depth: **23 – 183 m, ± 5m (75 - 600 ft)**

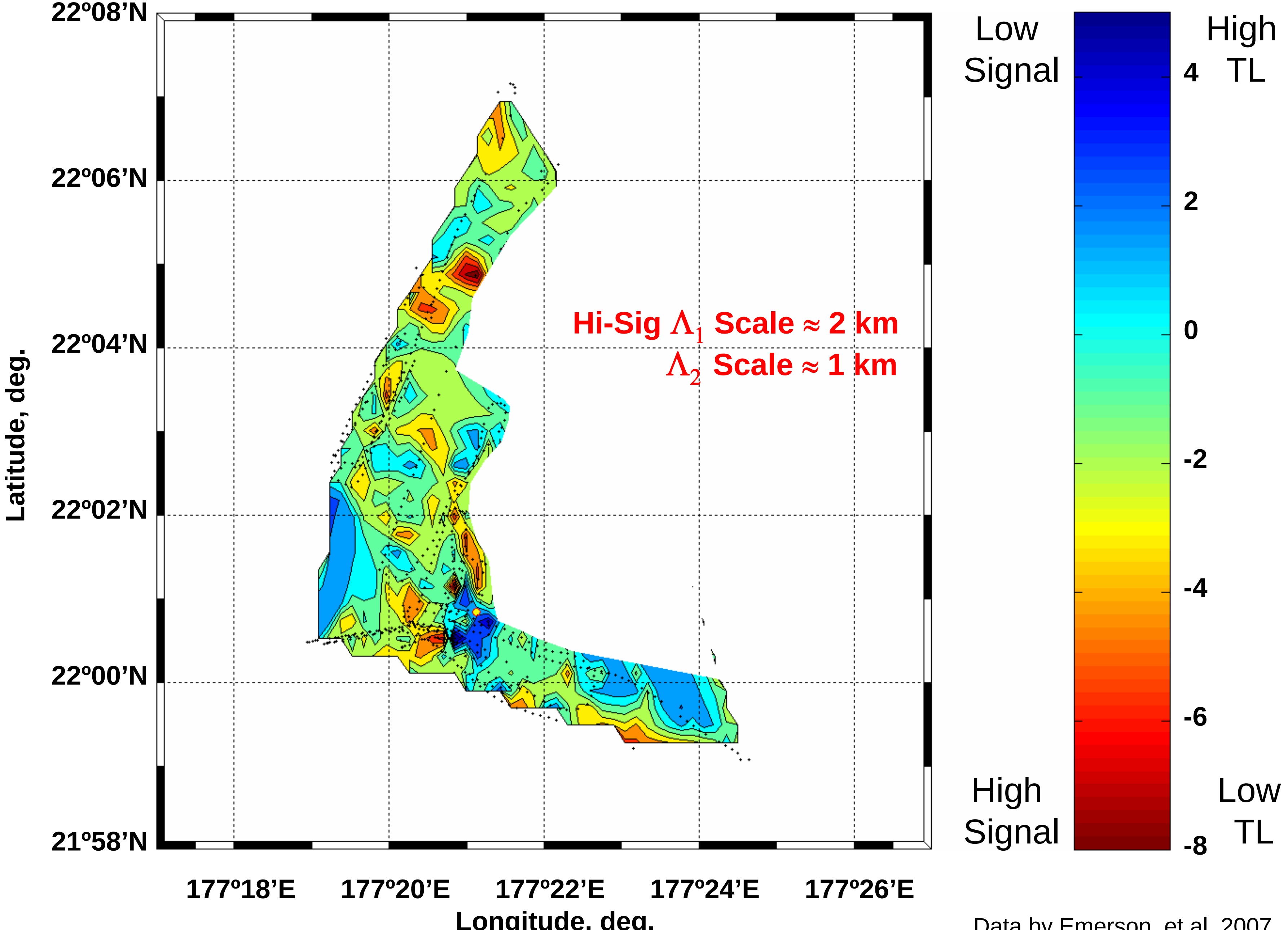
Speed: **1.5 – 4 m/s (3 - 8 Knots)**

Endurance: **3 to 6 hrs, Speed Dependent**

Launch: **Handheld**

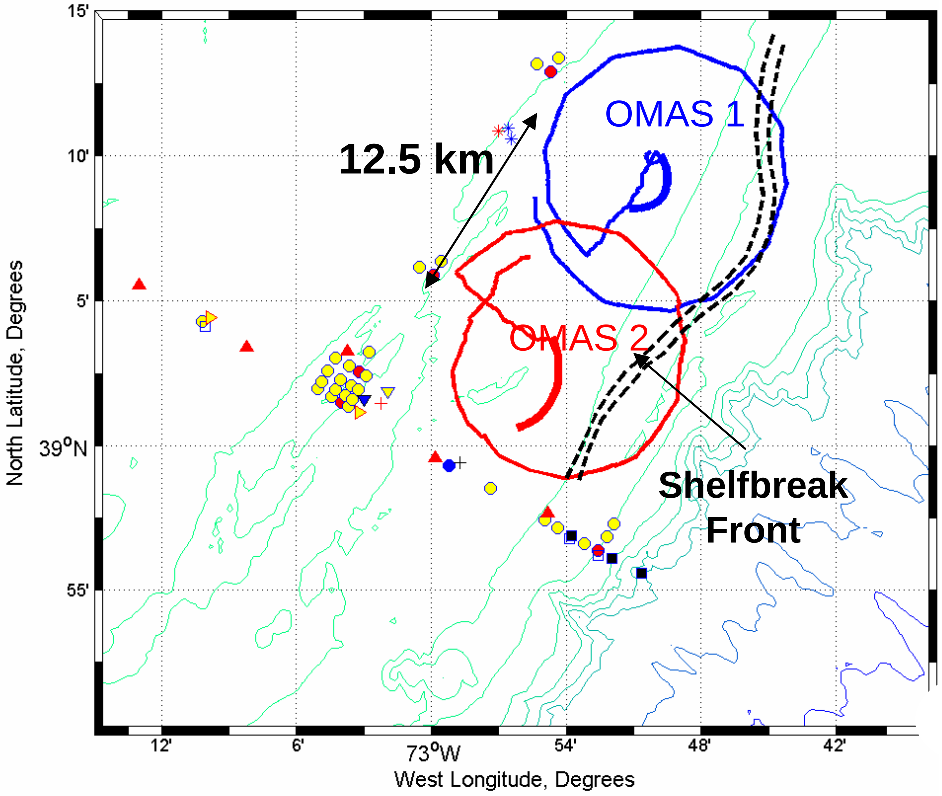
Range-Whitened Transmission on the SCS Shelf, 2005, D = 77 - 95 m, $\Delta\Theta$ = 7 hr

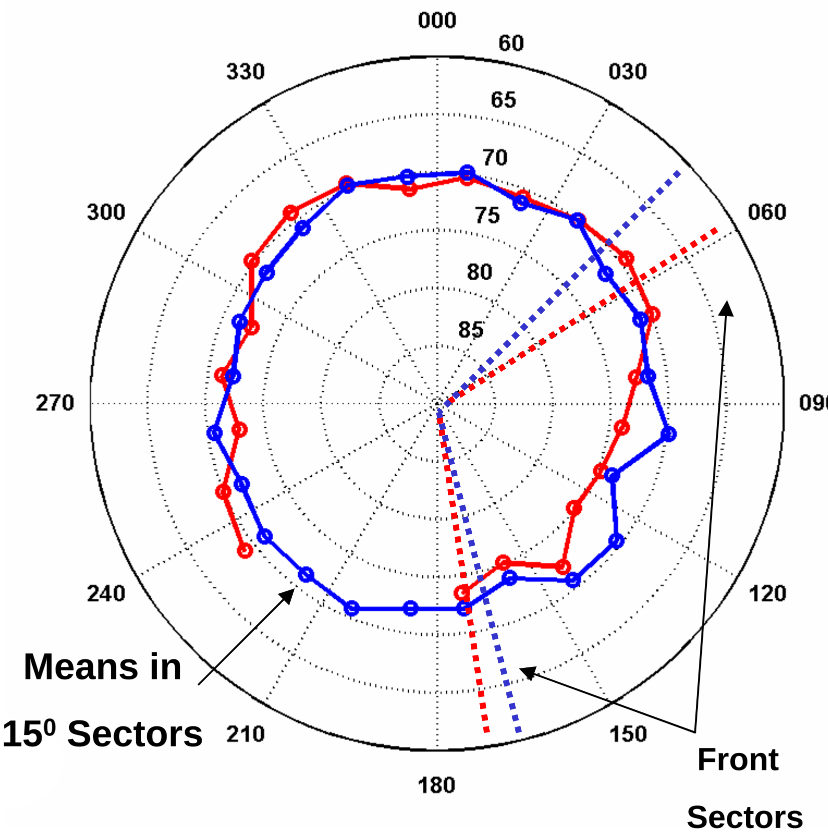
OMAS Sources 55 m, Moored Receiver 28.5 m, Replica Processed, f = 900 Hz



Data by Emerson, et al, 2007

Transmission Means in 15^0 Sectors vs β, at R = 7.5 km
NJ Shelf 2006, D = 80 - 120 m, f = 900 Hz, Replica Processed





For bearings excluding the front sectors, the mean $<\mu_{TL}>_\beta$ is horizontally isotropic, and translationally invariant for at least 12 km along the isobaths

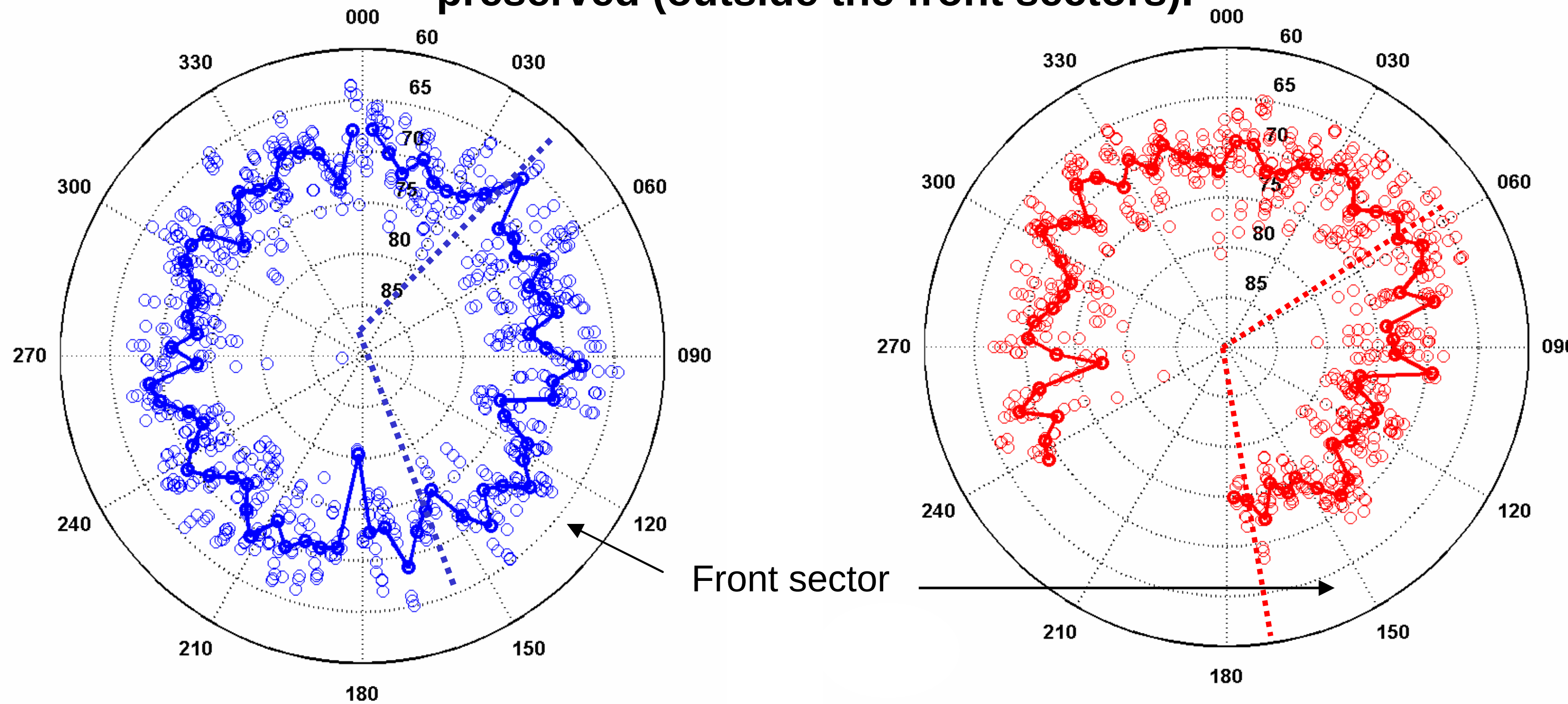
Data by Abbot, Emerson, Gedney

Transmission Means in 5^0 Sectors *vs* Bearing, at R = 7.5 km

NJ Shelf 2006, D = 80 - 120 m, f = 900 Hz, Replica Processed

The circumferential scale in each $\Lambda_2 \approx$ 1 km.

Isotropy and translational invariance is preserved (outside the front sectors).



An underlying structure of the acoustic field is resolved with 5^0 averaging. The environmental or other cause of this structure is as yet unknown.

Data by Abbot, Emerson, Gedney

ASSERTIONS/CHALLENGES IN SW ACOUSTICS II

Assertion: In shelf waters, real duct defects cause : 1) fluctuations around the mean transmission, with defect scale $\Lambda_2 \approx O$(1 km), and 2) scattering in all directions

Challenge 2: What is the physical explanation for the observed 1 km defect-scale? All SW defects referred to in this talk are plausible candidates, but none can be be ruled out unequivocally with the environmental data acquired. On the other hand, is the observed Λ_2 scale of O(1 km) simply the inherent period of the sound field, which itself is a complicated function of range?

Challenge 3: Defects are three-dimensional (3D) objects, and scattering itself is a 3D process. Thus, the 2D concepts now commonly in use for understanding and prediction need to be extended or replaced by 3D analytical/numerical approaches, such as surveyed by Robinson and Lee (1994), among others.

ASSERTIONS/CHALLENGES IN SW ACOUSTICS III

Challenge 4: Physical oceanography of shallow water, and ocean geology/geophysics of its bottom, have contributed, mainly by illuminating macroscale water-dynamics and bottom-roughness defects. But acoustics tests need to be supported also with quantitative real-time data on sea-surface roughness, below surface bubble clouds, and fish schools, *etc.*, each of which relate to significant defects.

Assertion: Macroscale defects in each class can be treated as perturbations in, as examples, deterministic 3D adiabatic or 3D refractive Fresnel-tube formulations.

Challenge 5: Deterministic analysis of small defects (microscale down to wavelength-scale) is not affordable, either intellectually or fiscally, and thus would need to be abandoned in favor of stochastic analysis. (The next slide suggests that distributions of small defects could be treated as multiple source functions that represent random scatterers.)

"DEFECTS" IN AN AIR-CONDITIONING DUCT

An aside based on Dyer,1958

- Transmission from a number, N, of δ-function spatially uncorrelated random acoustic sources was studied. These sources were distributed over the cross-section of an A/C duct of constant radius, r, and the field propagating in the duct was determined *vs* r.
- Conclusion: The lowest order modes (up to ~ ½ N) propagate with statistically equal acoustic intensity, *i.e.,* are "<u>energy-equipartitioned</u>", and are "<u>statistically independent</u>". This theoretical conclusion agrees with measured fan-driven noise in an A/C duct data (Kerka, 1957), in which the equipartitioned modes combine to match the observed radial dependence. (The underlined properties are classical features of the dynamics of multi-degree systems.)

ASSERTIONS/CHALLENGES IN SW ACOUSTICS IV

Assertion: In SW acoustics, <u>microscale</u> scattering defects act as N spatially uncorrelated random sources, with each proportional to the local primary sound field. N is the number of the more important small defects between receiver and source which, in most cases, would be local to the receiver. (The defects create a subsidiary 3D field of scattered acoustic waves, which are composed of ½ N equipartitioned modes, each with variance σ_d^2*. In the limit of large N,* σ_d^2 *would be approximately independent of depth, range, and bearing.)*

<u>Challenge 6</u>: What are the physical and computational limits that define the boundaries between macroscale and microscale defects?

<u>Challenge 7</u>: How should tests be designed, and data be analyzed, to distinguish out-of-plane losses due to scattering, from the commonly considered losses in the water and in the sediments?

ASSERTIONS/CHALLENGES IN SW ACOUSTICS V

Challenge 8: Because high-resolution temporal processing is already common in ocean acoustics, new or improved analytical/numerical tools also are needed to provide predictions in the time-domain. Path analysis comes to mind as a 3D possibility. Also the forward and backscattering full-wave analyses of Frankenthal & Beran (2006) for sound in a square duct, with time-dependent volume defects, could set the path toward analysis of the real SW duct. (For energy transport, a square duct in essence is a range-whitened version of the cylindrical duct herein designated as the canonical model.)

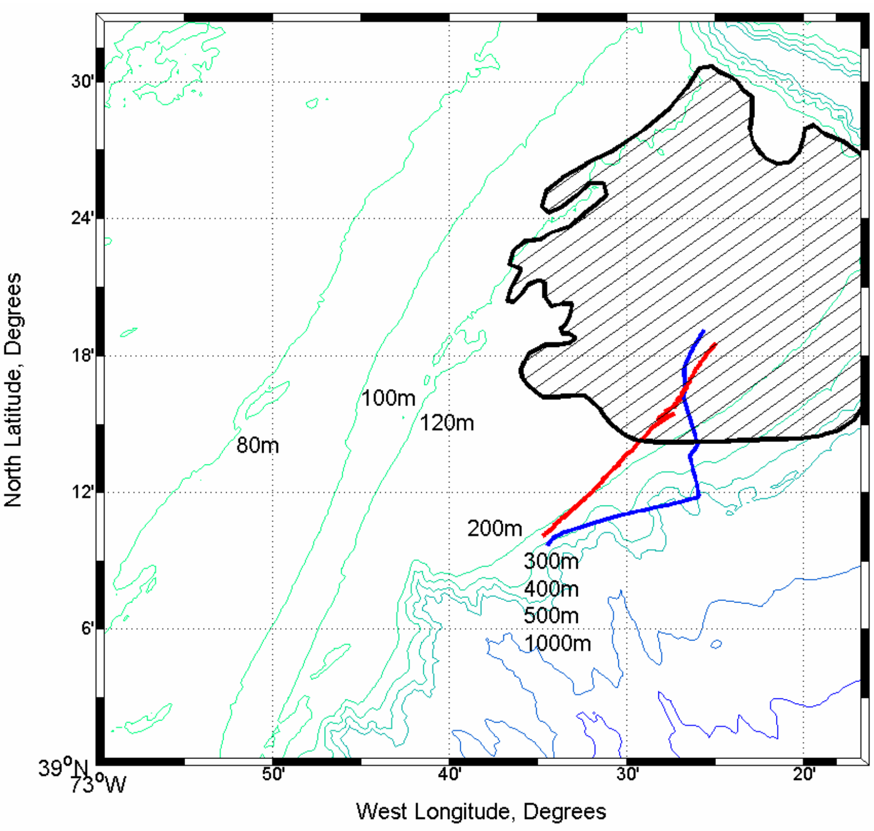
Summary Perspectives on the Acoustics of Shelf Waters

- Mean transmission of a sound wave in a shelf-water duct is robustly predicted by the canonical model; it represents the mean ocean environment, that is, with all defects erased or smoothed out
- Other than those due to phase-random summations of the sound field itself, transmission fluctuations are caused by defects; for most signal-processing methods, fluctuations due to the defects dominate
- A large defect can be analyzed as a perturbation of the mean
- A large number of small defects can be analyzed *via* the subsidiary sound field these defects generate by scattering
- This subsidiary field also can limit temporal and spatial coherence for passive sonar, and is the field that directly limits active sonar
- A reformulation of theoretical/numerical techniques that combine all of the foregoing would be ideally 4D (3D spatial, 1D temporal)
- Future at-sea tests would be ideally more inclusive of observations on all relevant defect classes, and of the diverse acoustic needs for the tests.

BEYOND THE SHELFBREAK

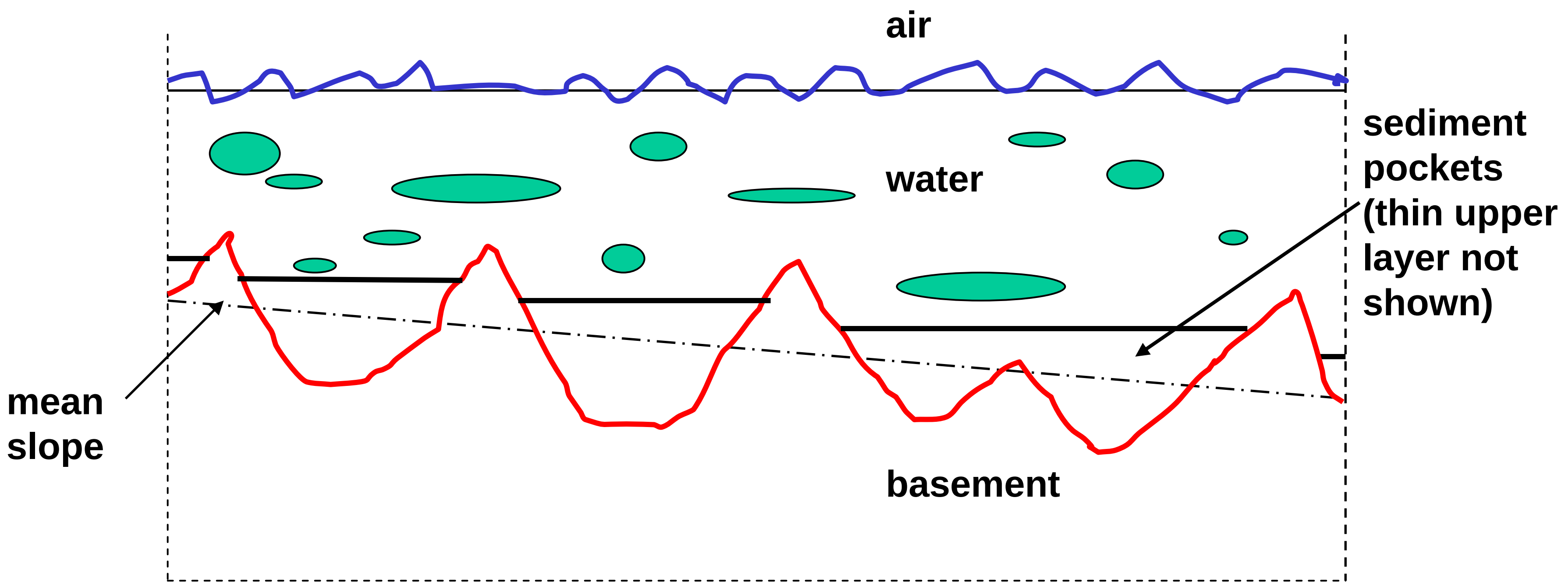
Assertion: The continental slope is acoustically more complicated than the continental shelf, even though the mean slope angle typically is < 4^0. Much less is known about defects on the slope compared to those on the shelf, and the retreat to averaging over bearing on the continental slope, to attain some degree of simplicity and general understanding, is patently a poor approach.

The Continental Slope is Significantly Different Acoustically Than the Shelf



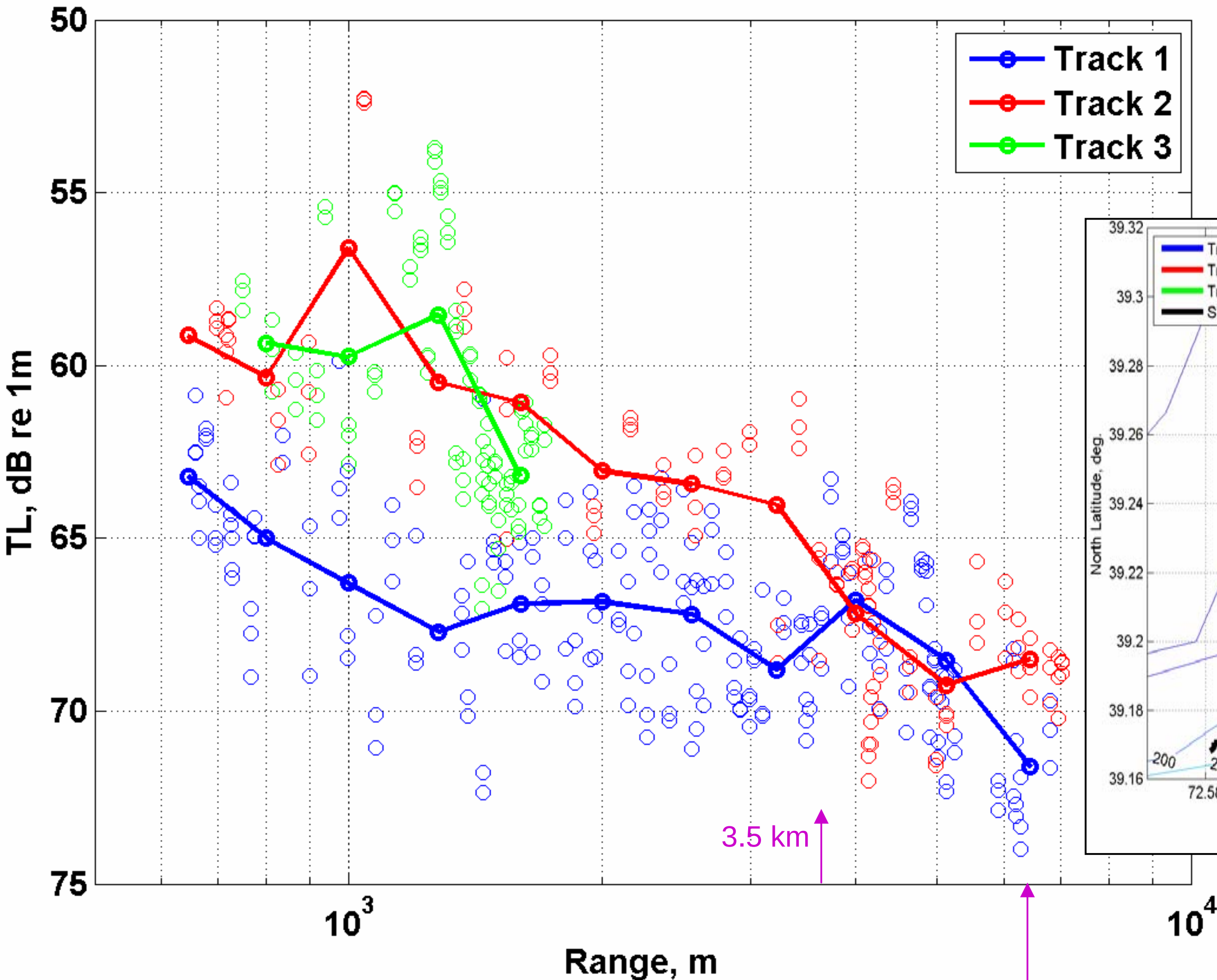
THE REAL ACOUSTICS DUCT FOR SLOPE WATERS

Shown in a Transmission Plane Normal to the Isobaths

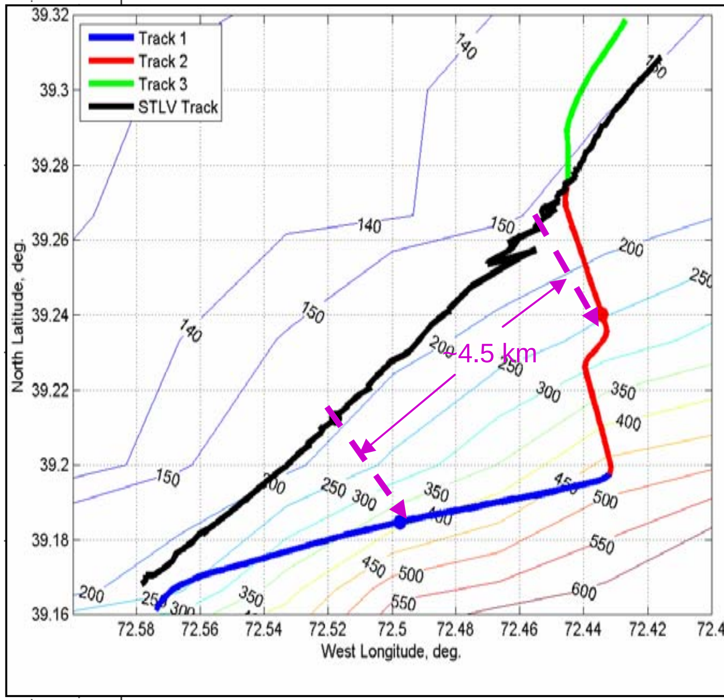


Typical mean angles on the continental slope are 1^0 to 4^0, with bottom defects similar to those on the shelf, but more dramatic and complicated by basement outcrops that dam the downward transport of sediments. Because a plane parallel to the isobaths has constant water depth, it is more like the real shelf duct, but transmission can be interrupted, or channeled, by outcrops.

Measured Transmission (peak replica processing) *vs* Receiver Track, OMAS Source on NJ Shelf (Black Track), Receiver on Slope or Shelf



Translational Invariance on Slope ≈ 4.5 km

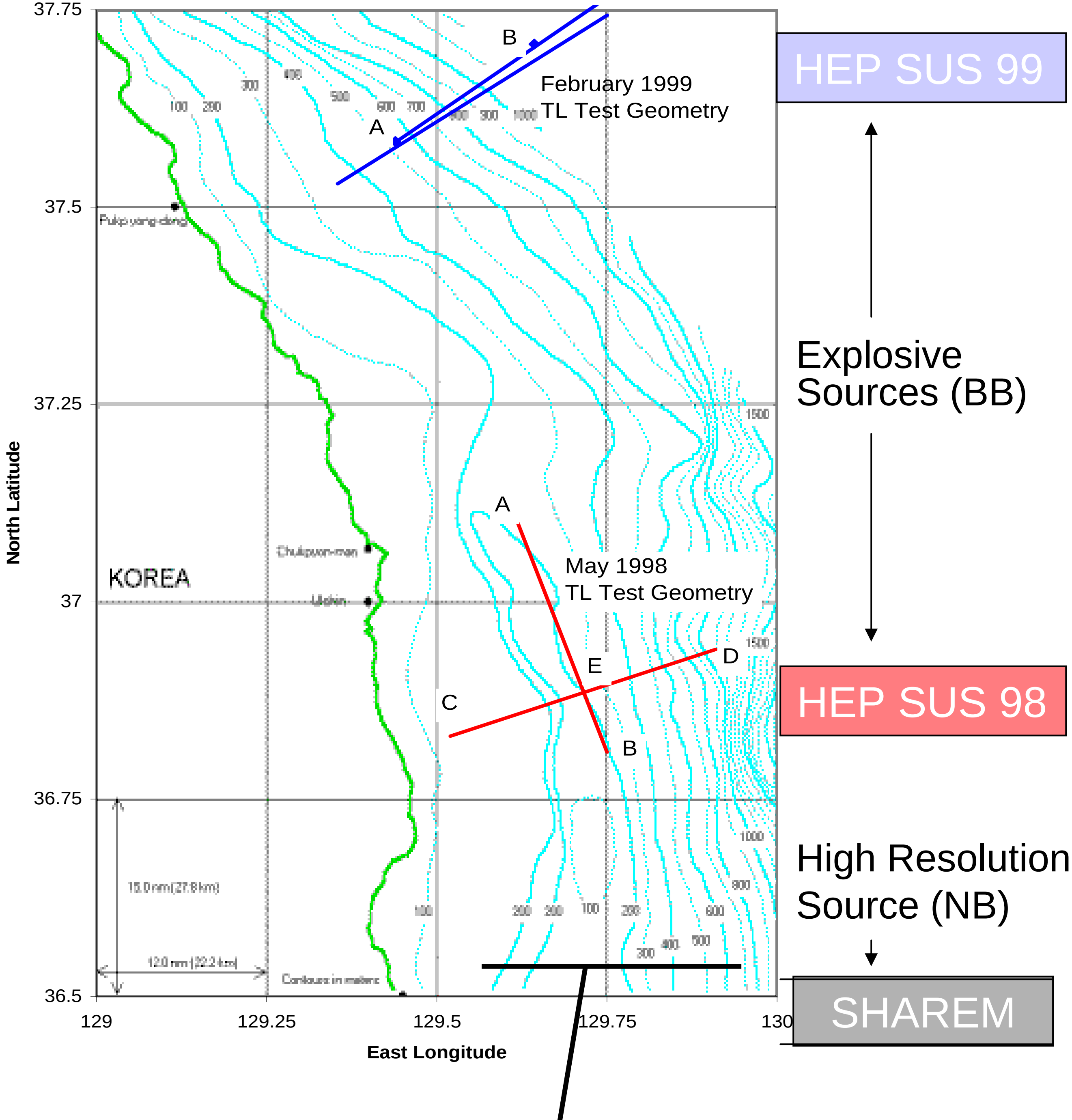


N = 210 **σ = 2.1 dB**	**N = 81** **σ = 2.6 dB**	**N = 108** **σ = 2.2 dB**

Slope outcrop between Tracks at R = 7 km ?

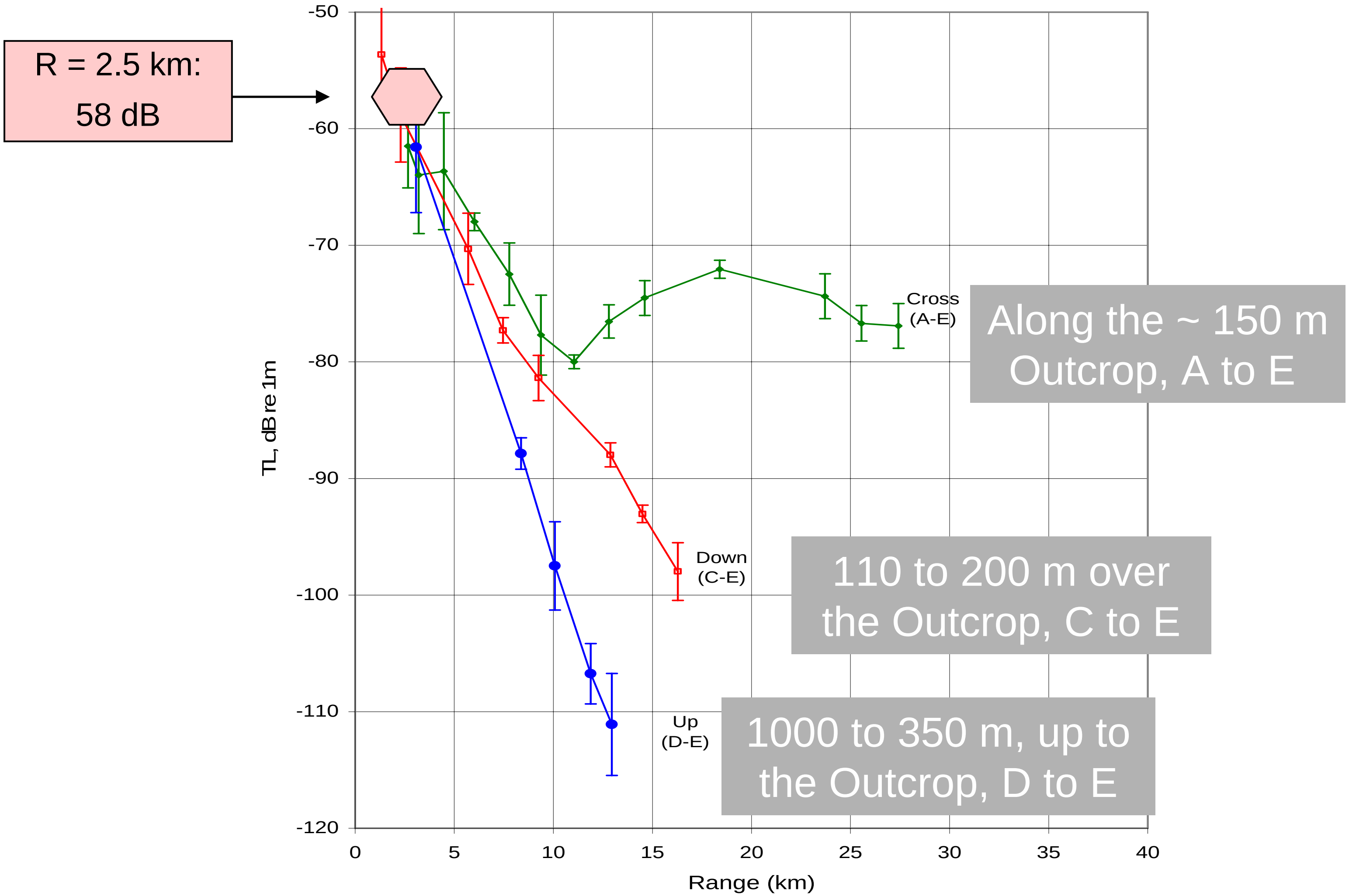
Data by Abbot, *et. al.*

Transmission on the Continental Slope in the Sea of Japan



HEP BB SOJ Slope Transmission, May 1998

SUS Sources, 400 Hz Octave, $d_s = d_r = 18$ m

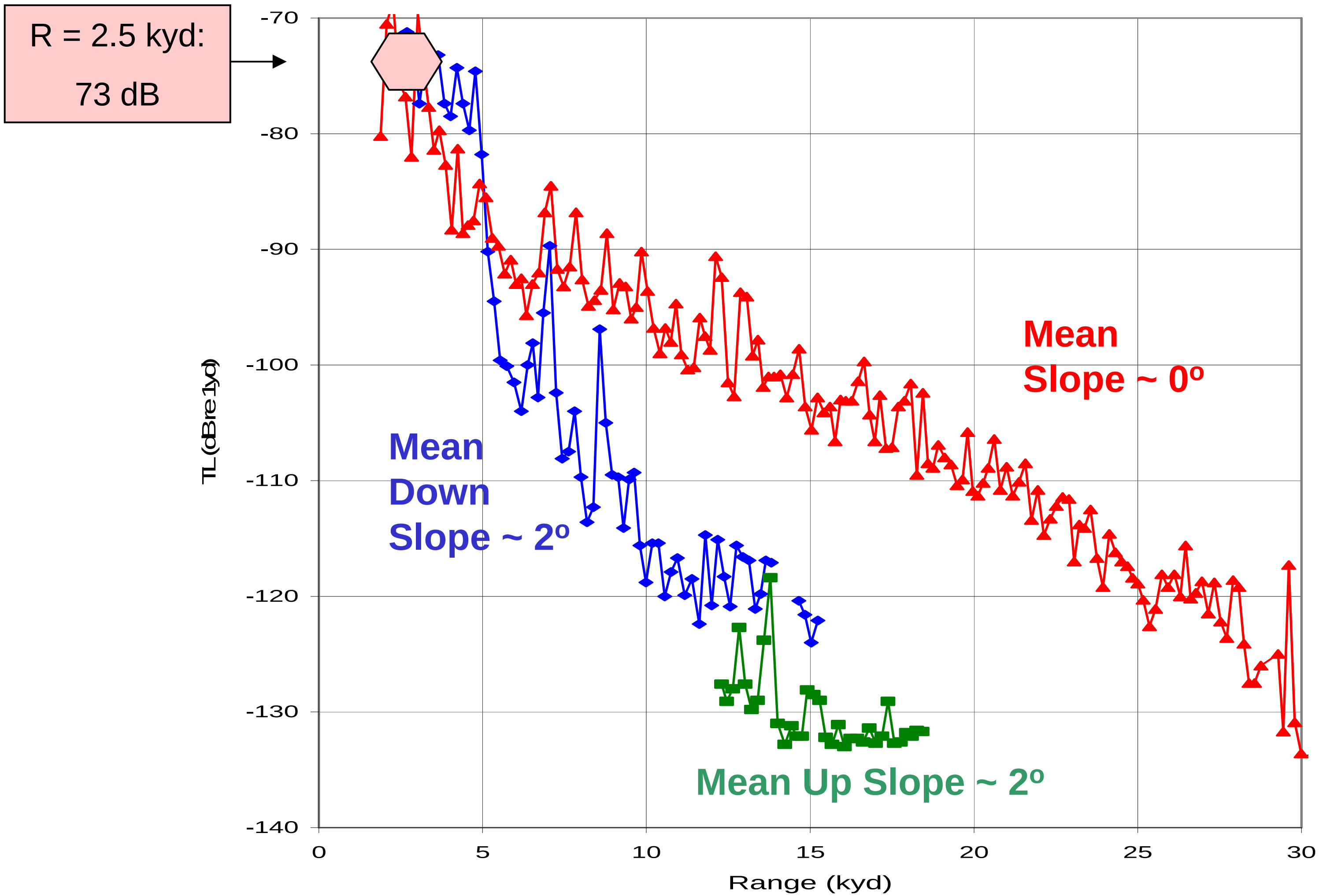


From Abbot, Dyer, & Celuzza

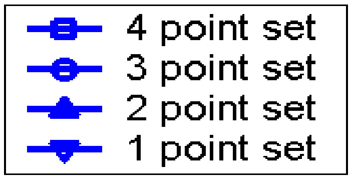
SHAREM NB SOJ Slope Transmission

d_s = 8 m, d_r = 53m, f = 3.5 kHz, Replica Processed

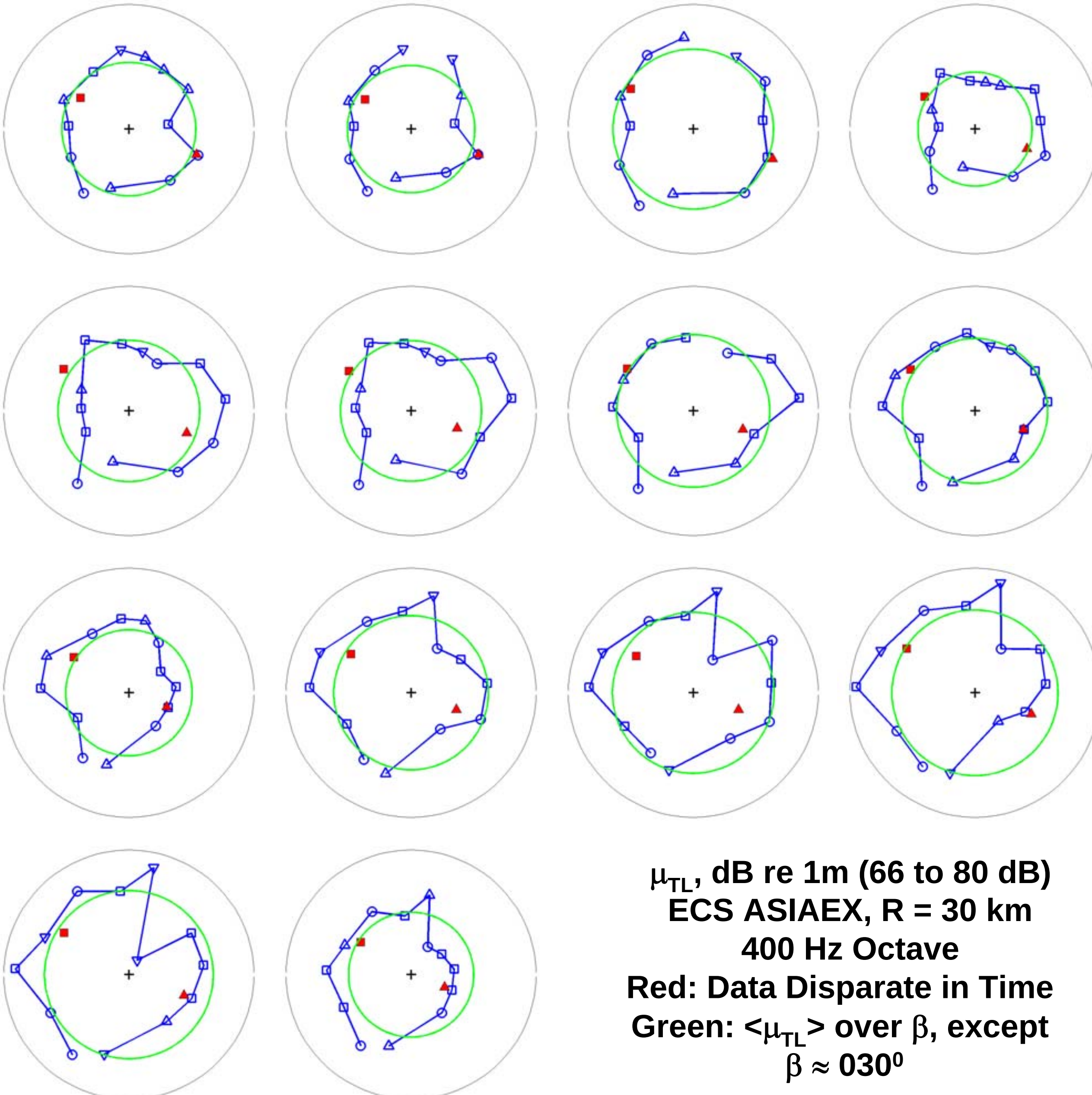
Red: Parallel, Blue: Normal, Down Slope, Green: Normal, Up Slope



Smoothed & Assimilated Transmission: μ_{TL}, dB re 1 m



Upon excluding the anomaly at $\beta \approx 030^0$, the mean μ_{TL} is approximately isotropic (green circles), but variations in β remain



μ_{TL}, dB re 1m (66 to 80 dB)
ECS ASIAEX, R = 30 km
400 Hz Octave
Red: Data Disparate in Time
Green: $<\mu_{TL}>$ over β, except $\beta \approx 030^0$

from Abbot, Dyer, & Emerson, 2006