A long time series of upper-ocean turbulent dissipation from a deep-ocean surface mooring equipped with Nortek HR Profilers

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Outline:

→Introduction: Conventional turbulence measurements in the open ocean

→Turbulence measurements with an Aquadopp HR-Profiler on a surface mooring:
    →Why use an HR-Profiler?
    →Approach
    →Processing and measurement noise
    →Results: 9-months of turbulent dissipation at an open-ocean site

Conventional approach to open-ocean turbulence measurements

→Free-fall microstructure profilers deployed from ships (e.g., Oakey, 1982; Moum et al., 1995; Gregg, 1998)

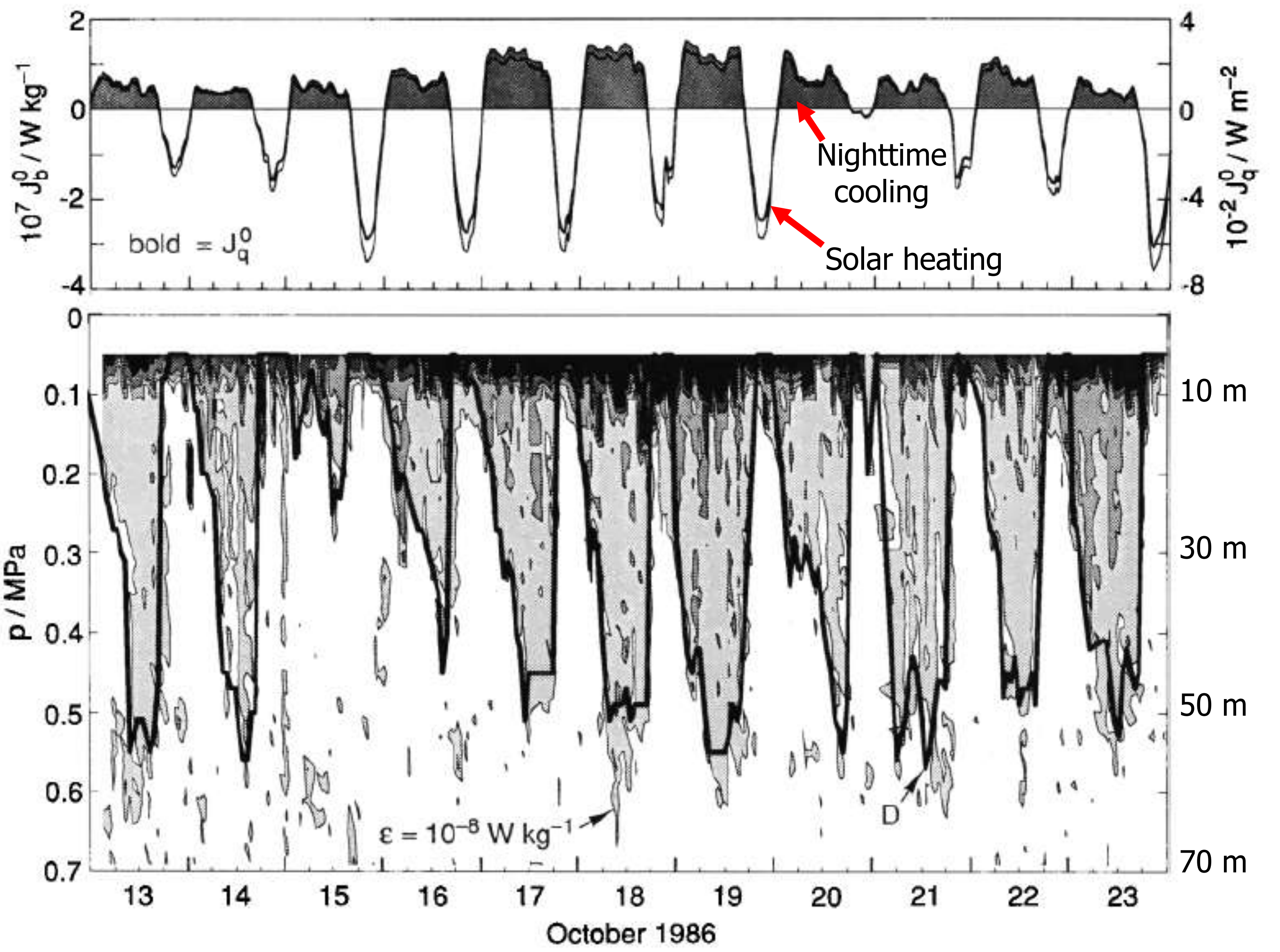
→Typical sensor package:
  - →CTD
  - →2 fast-response micro-temperature probes
  - →2 micro-shear probes

→These ship-based measurements are expensive. (Ships cost >$20k/day and the measurements require ~3 people working around the clock.)

→Typical data sets are 2 weeks long.

A typical 11-day data set (Lombardo and Gregg, 1989)

LOMBARDO AND GREGG: SIMILARITY SCALING DURING NIGHTTIME CONVECTION



Nighttime cooling

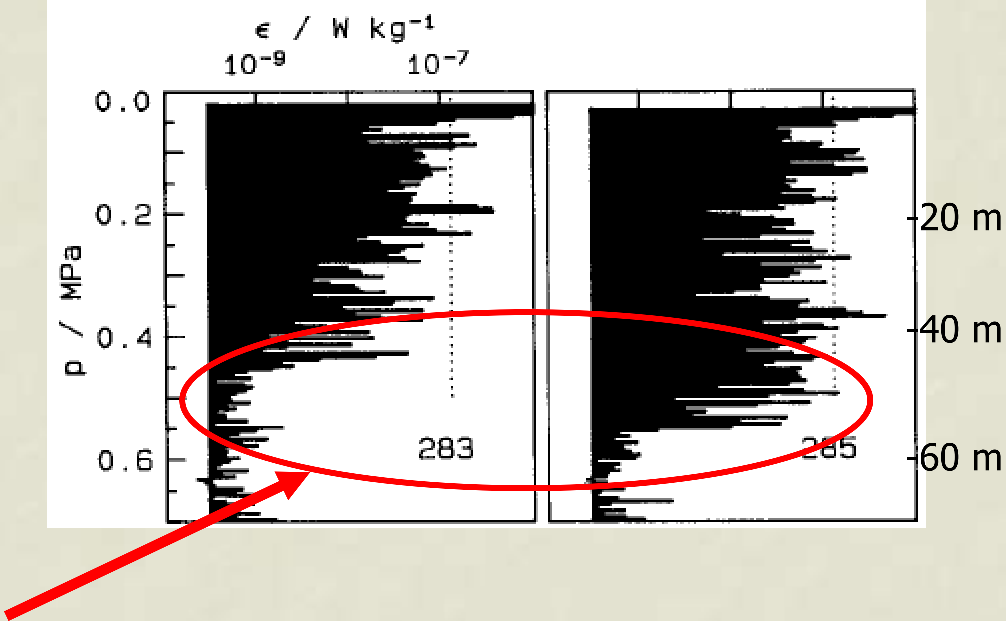
Solar heating

Surface heat flux (units of 100 W/m^2)

Turbulent kinetic energy dissipation

Turbulence is patchy and episodic

Two dissipation estimates from casts 7 minutes apart
(from Shay and Gregg, 1986):



Dissipation varies by a factor of ~100 between the two casts, for no obvious reason other than the intermittency of turbulence

→We need a way of making sustained, time-series measurements!

Turbulence measurements from a surface mooring

→We need sustained time-series measurements of turbulence properties (like turbulent dissipation).

→To understand those measurements, we also need time series of:

(1) Surface forcing (e.g., heat flux, wind stress)
(2) Surface waves
(3) Evolution of non-turbulent temperature, salinity, and velocity

→Ideally, we'd like all of these measurements sampled at once/hour for many months.

Turbulence measurements from a surface mooring

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→Ideally, we'd like all of these measurements sampled at once/hour for many months.

→There is really only one way to do all of this: use a surface mooring, with a buoy anchored to the sea floor.

→People have been pursuing this for some time using conventional microstructure-profiler techniques (e.g., Lueck et al., 1997; Moum and Nash, 2009).

→There are some serious difficulties related to mooring motion.

Pulse-coherent Doppler sonar for turbulent dissipation on a surface mooring

Advantages:

→A major virtue is that the spatial fluctuations of velocity can be estimated without using the frozen-field approximation.

→A sample can take only ~1 ms to collect. This helps avoid errors due to platform motion.

Things to worry about:

(1) The turbulent wake of the mooring.

(2) The time taken to make a profile estimate needs to be as short as possible to avoid "smearing" the small-scale turbulence.

(For example, if pings are averaged over ¼ sec and mean flow is 40 cm/s, the minimum resolved length scale is 10 cm.)

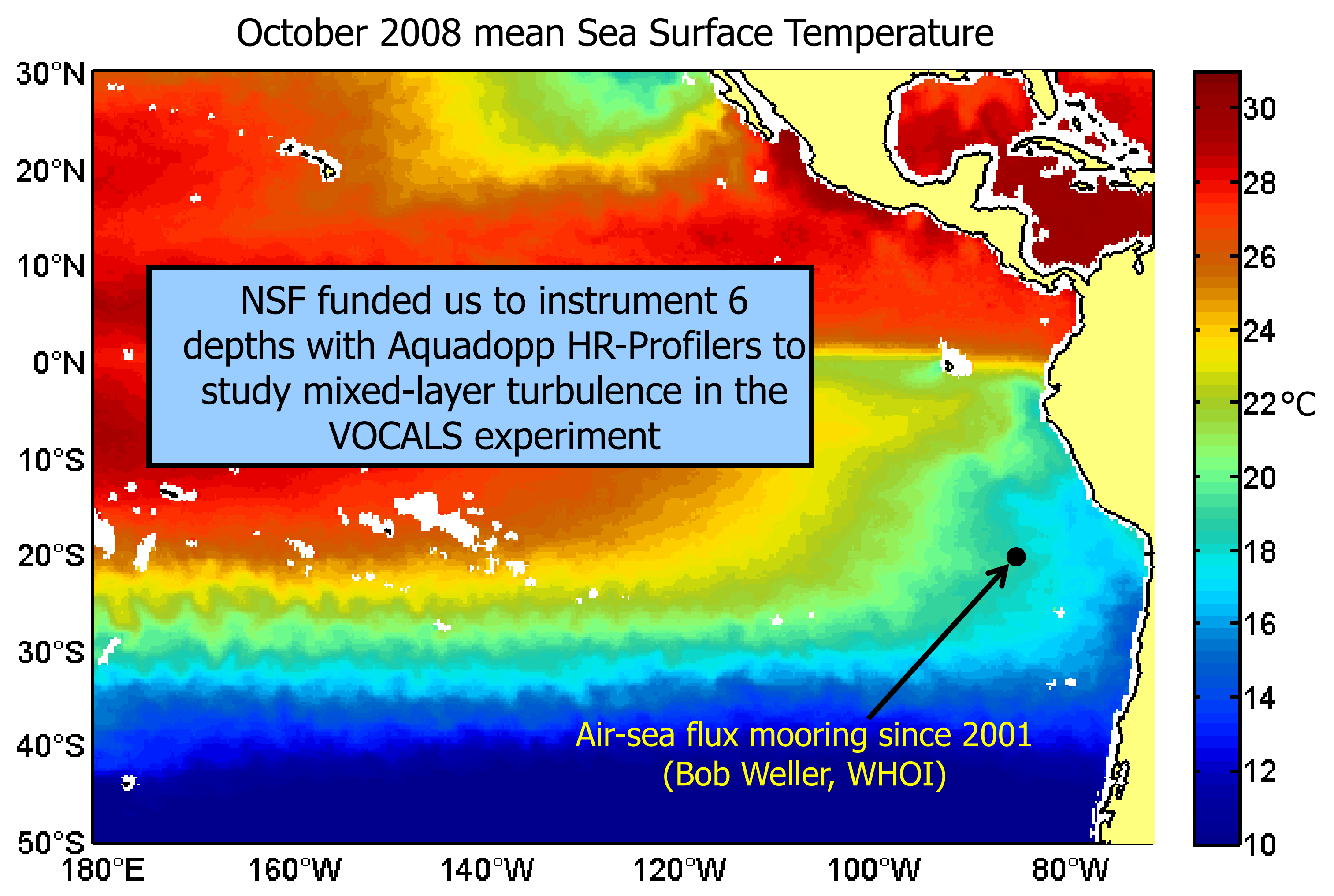
(3) The turbulent velocity fluctuations in the open ocean are *very* weak (< 1 cm/s)

(4) There is a tradeoff between length of profile (i.e., range) and the maximum velocity that can be unambiguously measured.

(This is because the instrument actually measures a phase shift between returned signals.)

VOCALS-REx: "VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment"

→Primary oceanographic goal: Understanding why SST is cool in the Southeast Pacific



NSF funded us to instrument 6 depths with Aquadopp HR-Profilers to study mixed-layer turbulence in the VOCALS experiment

Air-sea flux mooring since 2001
(Bob Weller, WHOI)

SST data: AMSRE satellite microwave, courtesy of Remote Sensing Systems

Pulse-coherent Doppler sonar for turbulent dissipation on a surface mooring

2 MHz Aquadopp HR-Profiler:
A single horizontal beam measures a ~1.5-m profile with ~3-cm resolution, which can be used for inertial-subrange estimates of dissipation (i.e., fitting a -5/3 power law to velocity spectra)

As we configured them, the instruments made a single velocity <u>profile estimate in about 2 ms</u> and averaged 20 of these estimates into <u>¼ second ensembles.</u>

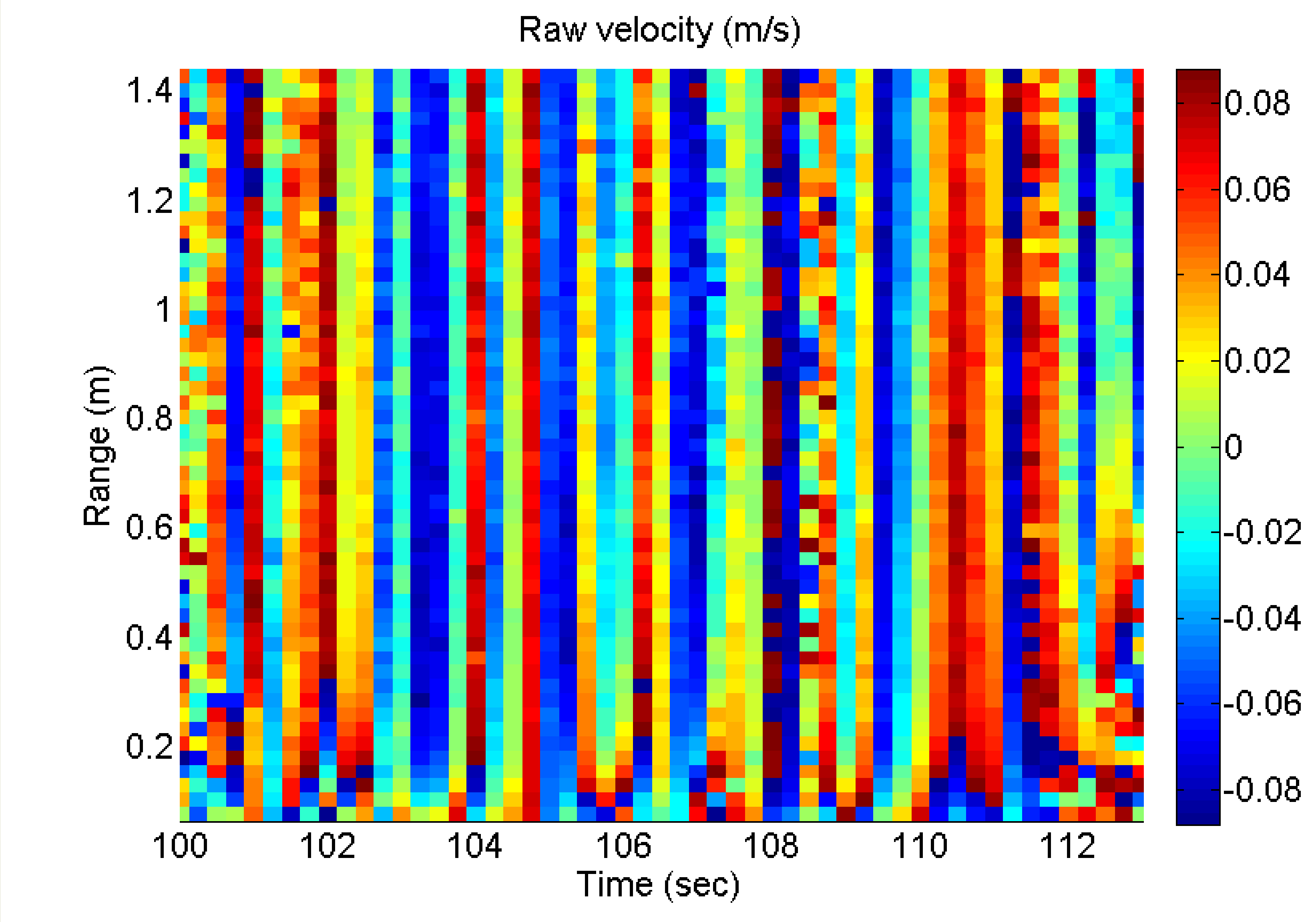
With the extended housing and extra data logger, the instruments collected about 540 profiles at 4 Hz, every hour for one year.

Pulse-coherent Doppler sonar for turbulent dissipation on a surface mooring

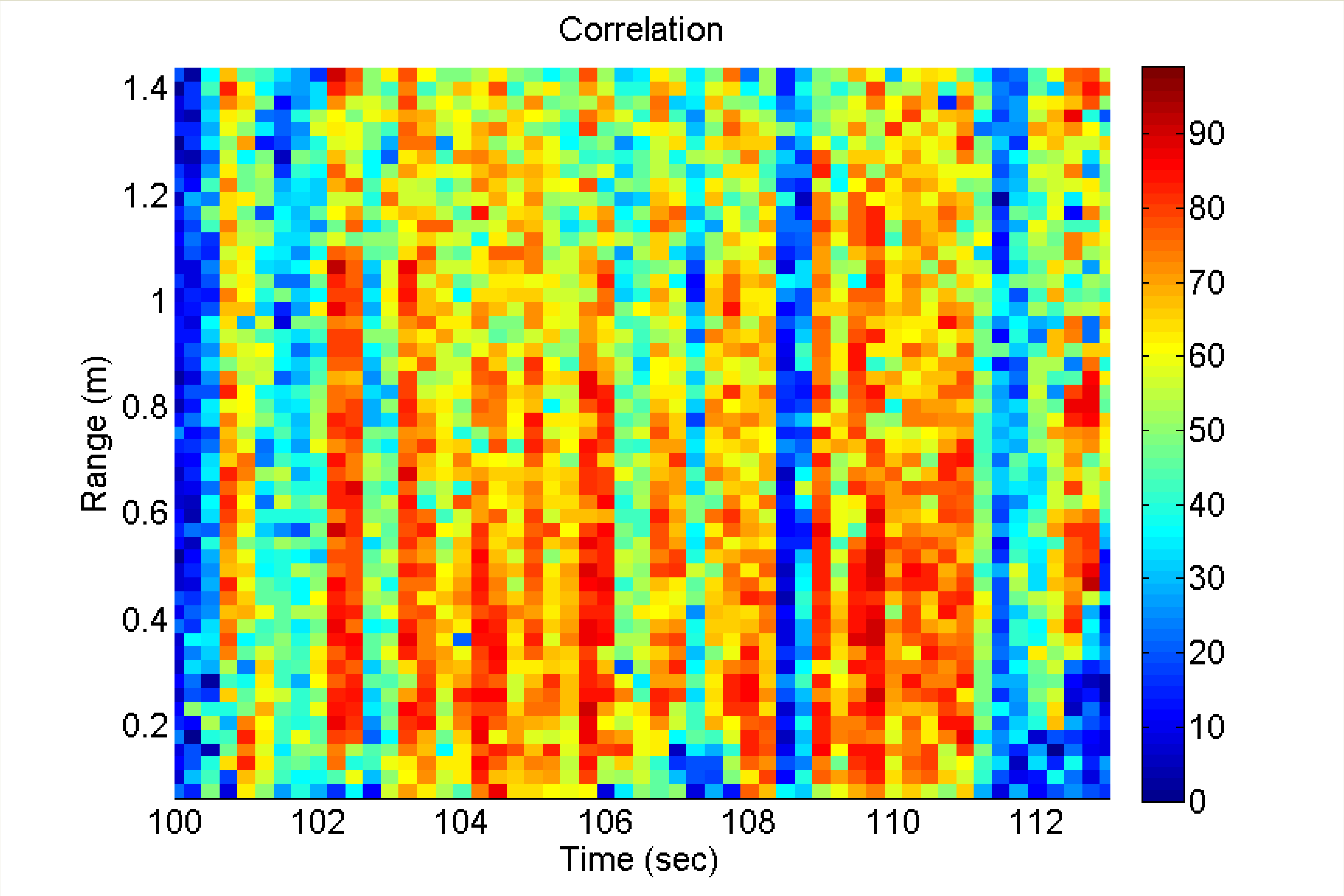
We deployed these instruments at 6 depths in the upper 100 m. 5 out of 6 instrument pairs came back looking like this.

We did get good data from an instrument pair at 8.4-m depth (above the spot where the mooring broke).

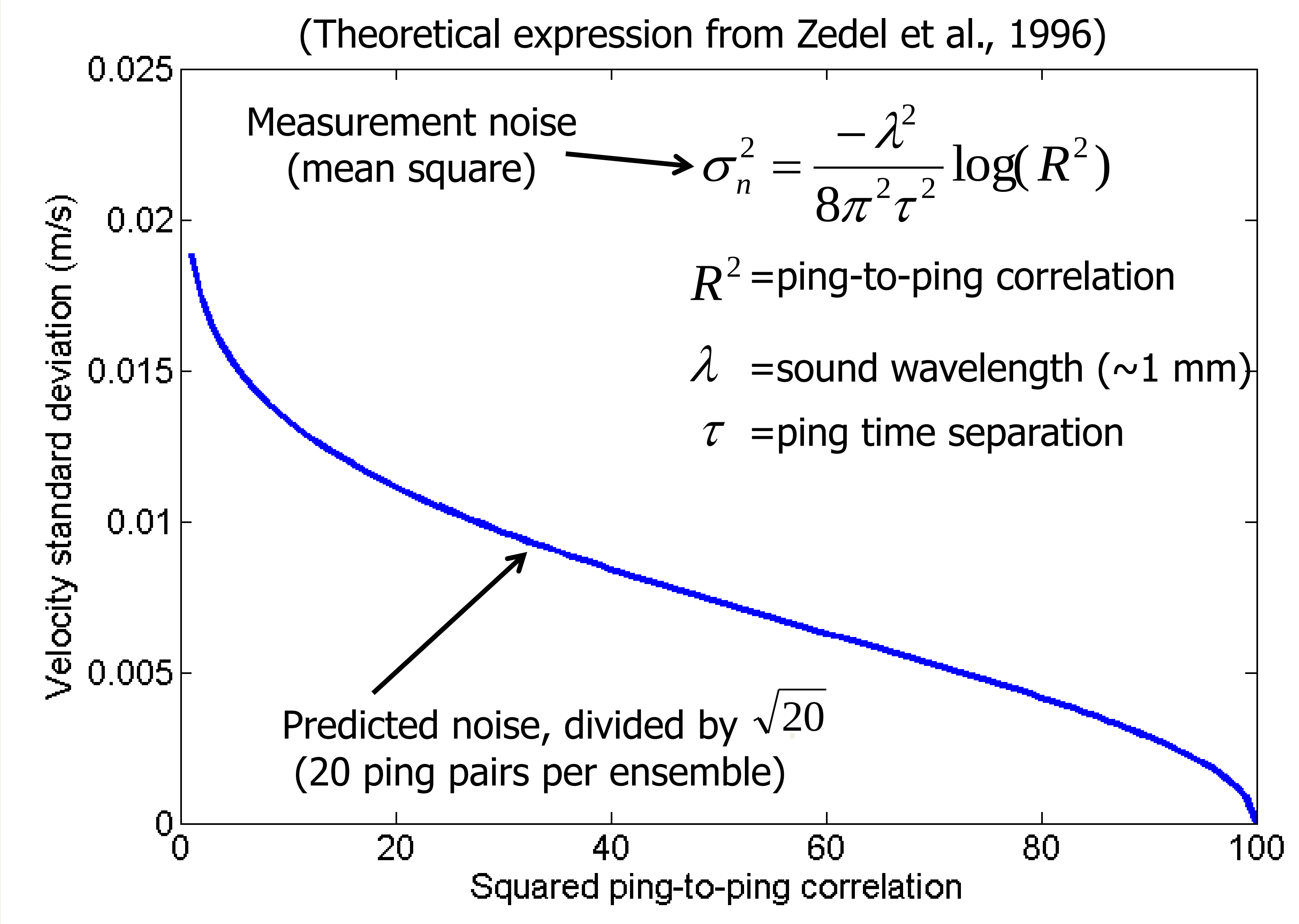
13 seconds of data: stepping through quality control



13 seconds of data: Measured correlation is a key parameter



Theoretical measurement noise as a function of measured ping-to-ping correlation



(Theoretical expression from Zedel et al., 1996)

Measurement noise (mean square) →

$$\sigma_n^2 = \frac{-\lambda^2}{8\pi^2\tau^2}\log(R^2)$$

R^2 =ping-to-ping correlation

λ =sound wavelength (~1 mm)

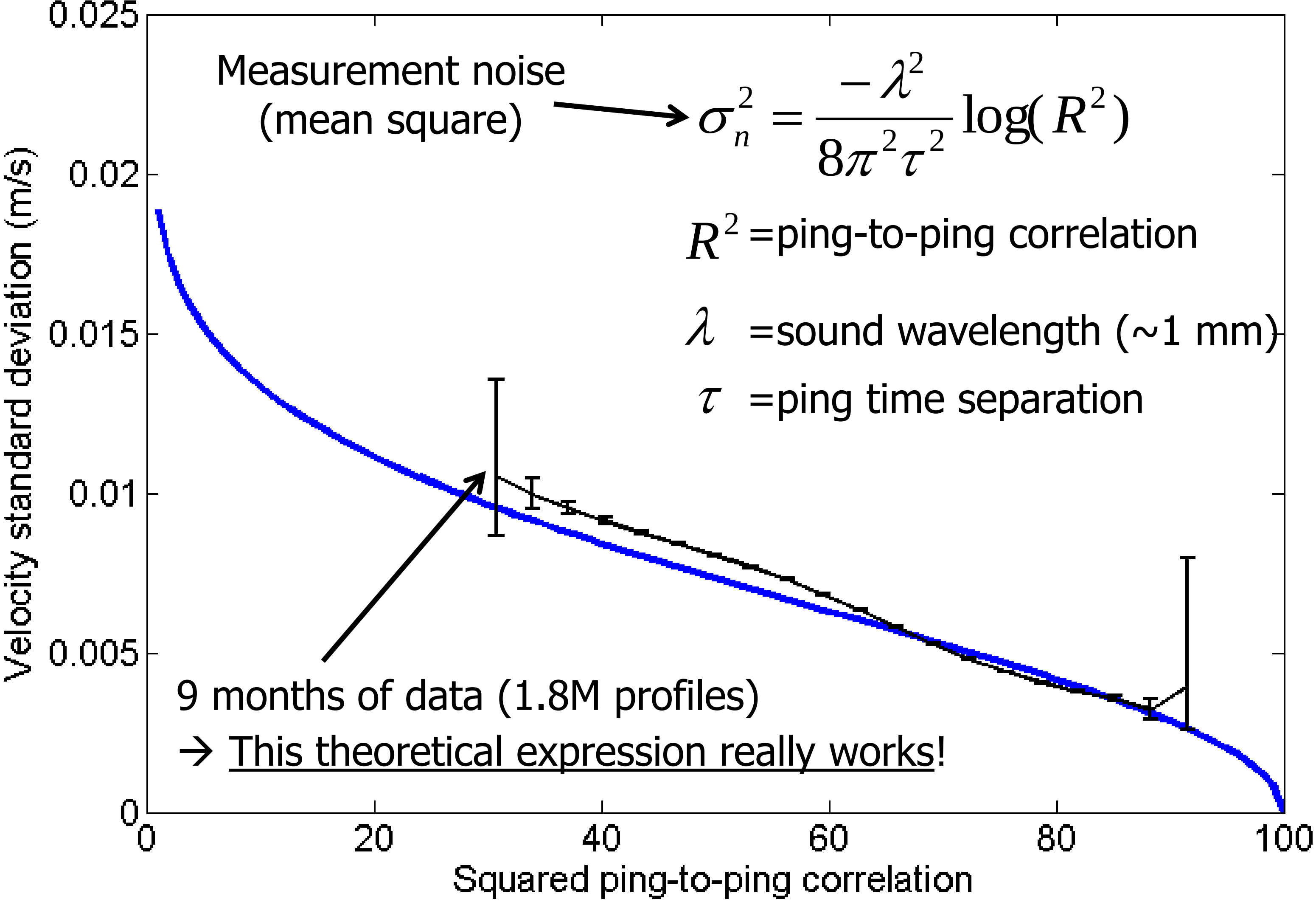
τ =ping time separation

Predicted noise, divided by $\sqrt{20}$

(20 ping pairs per ensemble)

Theoretical measurement noise as a function of measured ping-to-ping correlation

(Theoretical expression from Zedel et al., 1996)



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$$\sigma_n^2 = \frac{-\lambda^2}{8\pi^2\tau^2}\log(R^2)$$

R^2 =ping-to-ping correlation

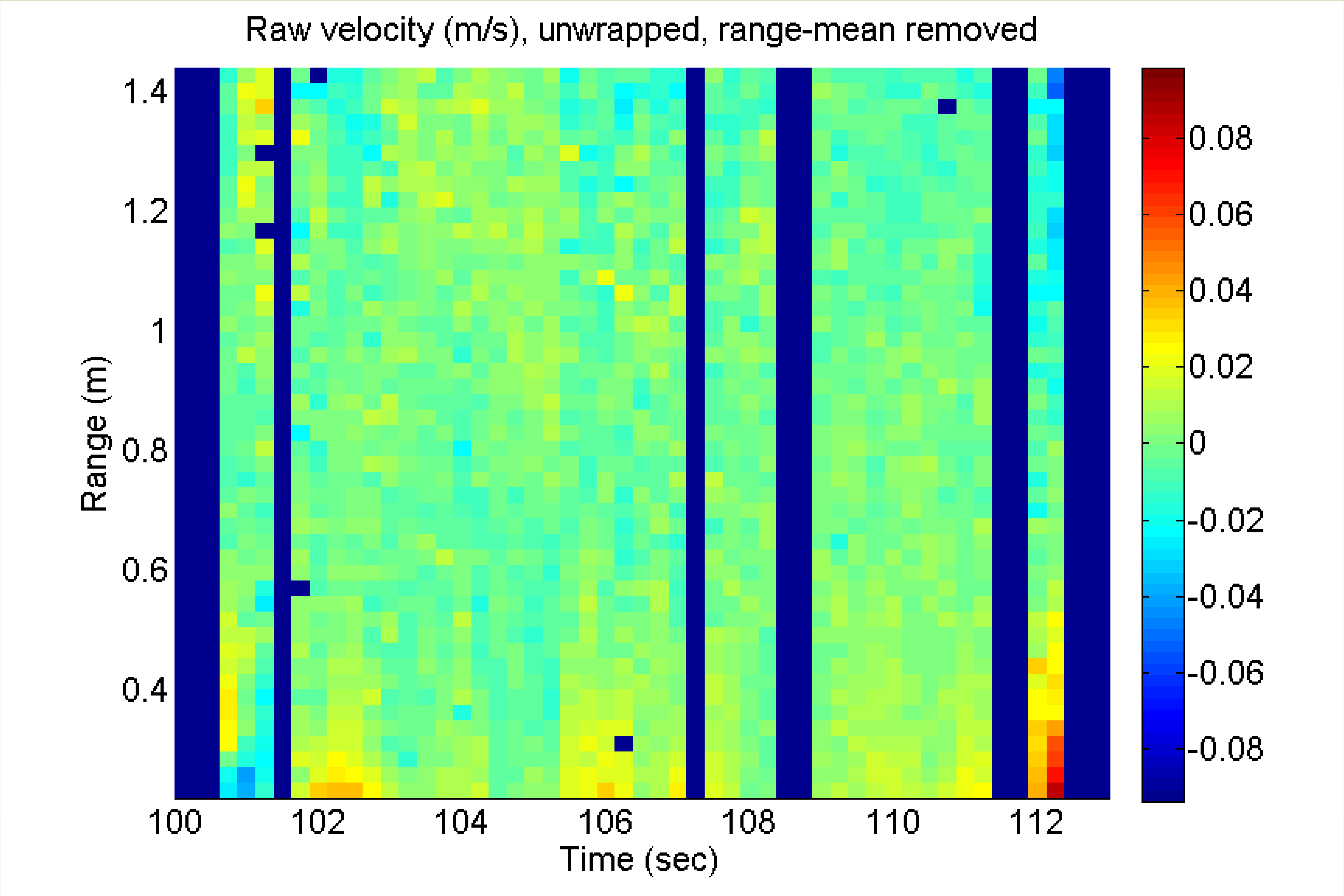
λ =sound wavelength (~1 mm)

τ =ping time separation

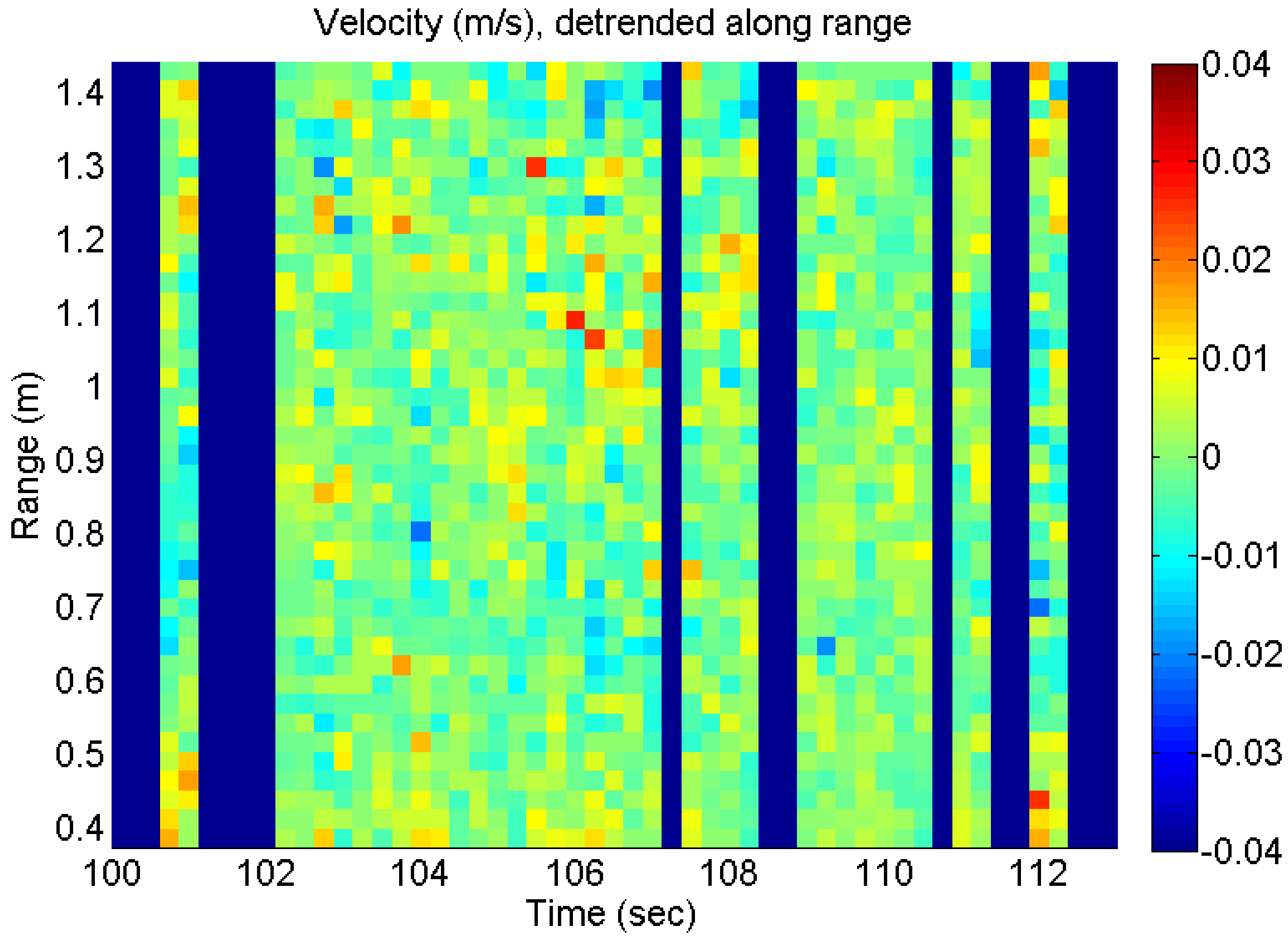
9 months of data (1.8M profiles)

→ <u>This theoretical expression really works</u>!

13 seconds of data: low correlations excluded, data unwrapped



13 seconds of data: after initial quality control



Estimating dissipation using an "inertial subrange" fit

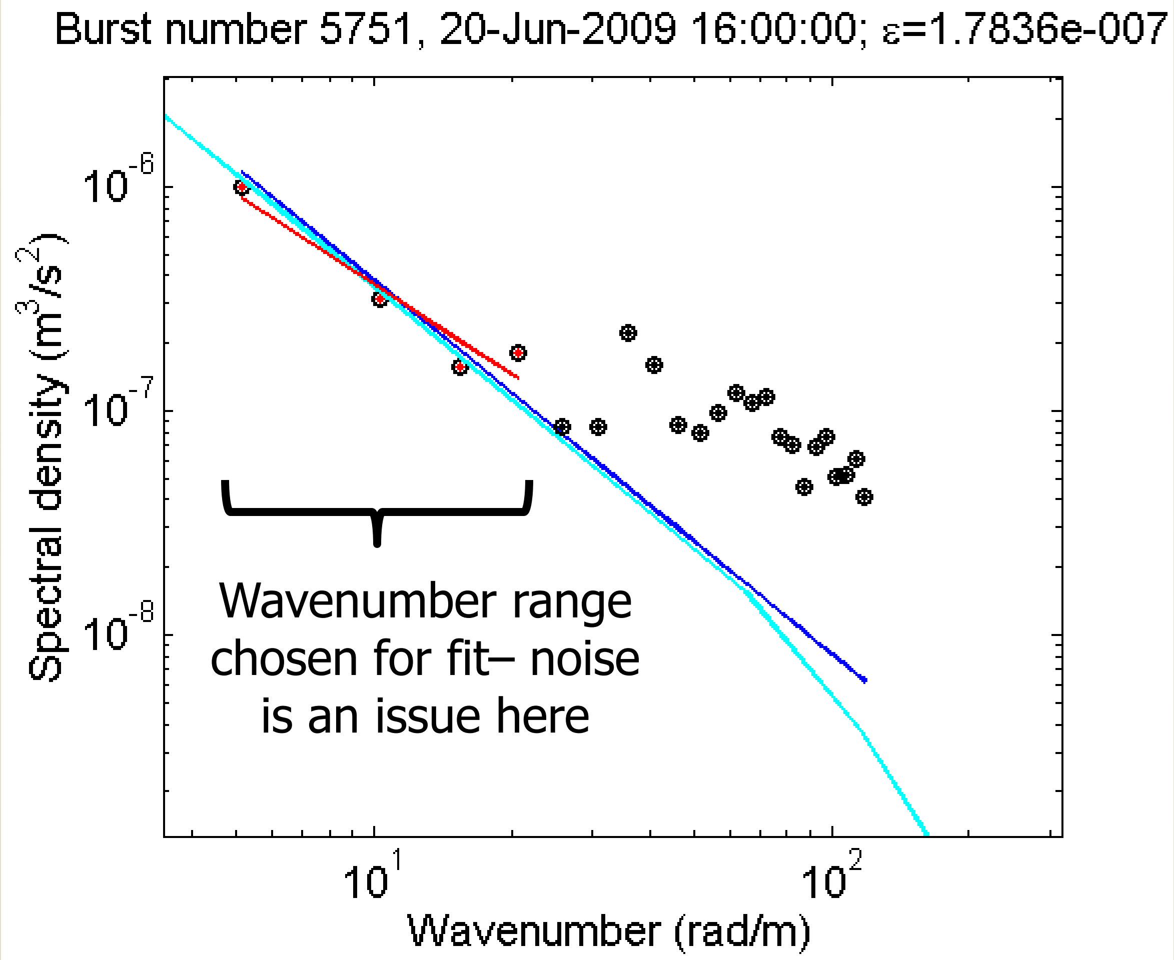
$$\Psi(k) = A\varepsilon^{2/3}k^{-5/3}$$

k =wavenumber (i.e., 2π/wavelength)

A=constant, ~0.557

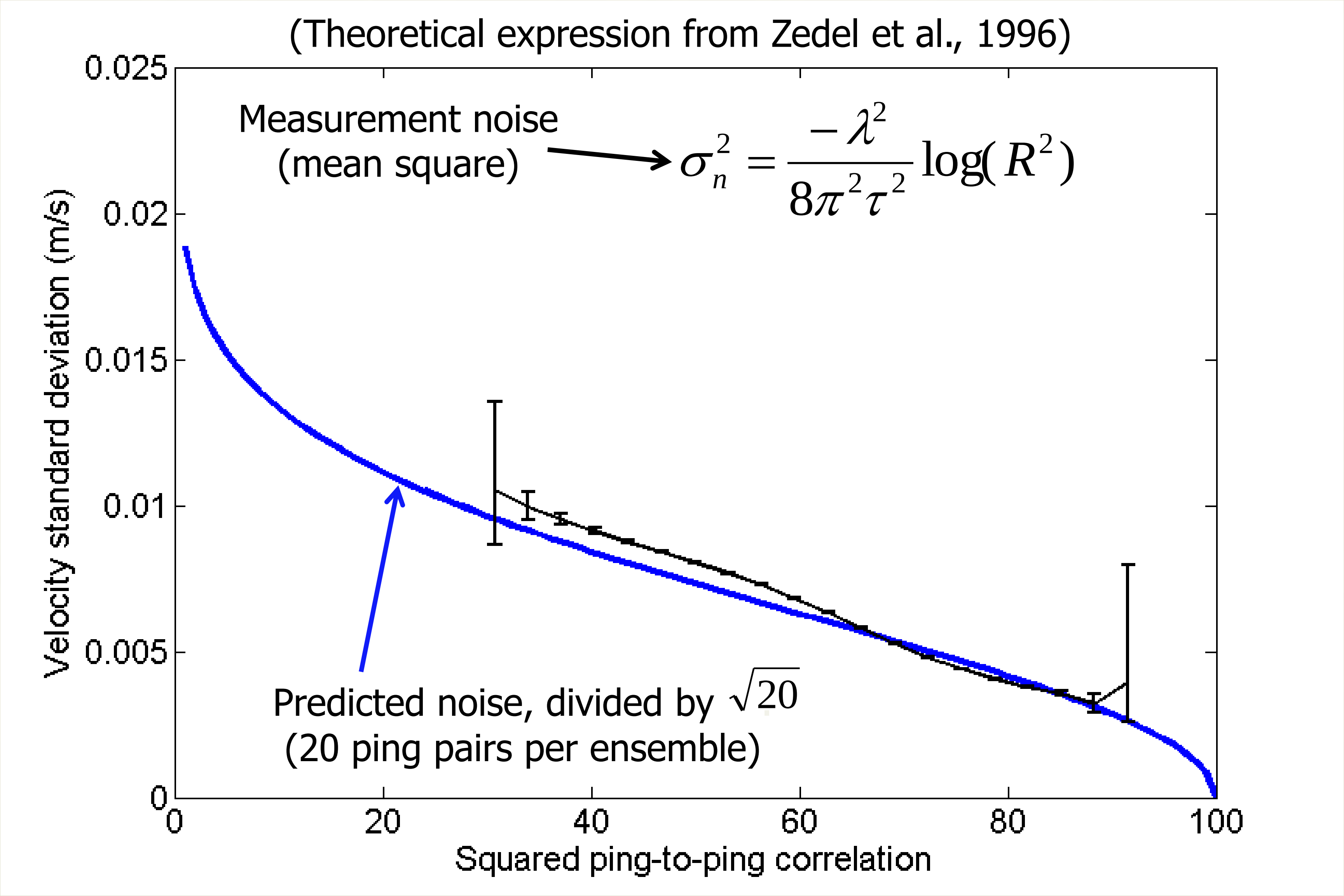
ε =turbulent dissipation

Ψ =velocity spectrum



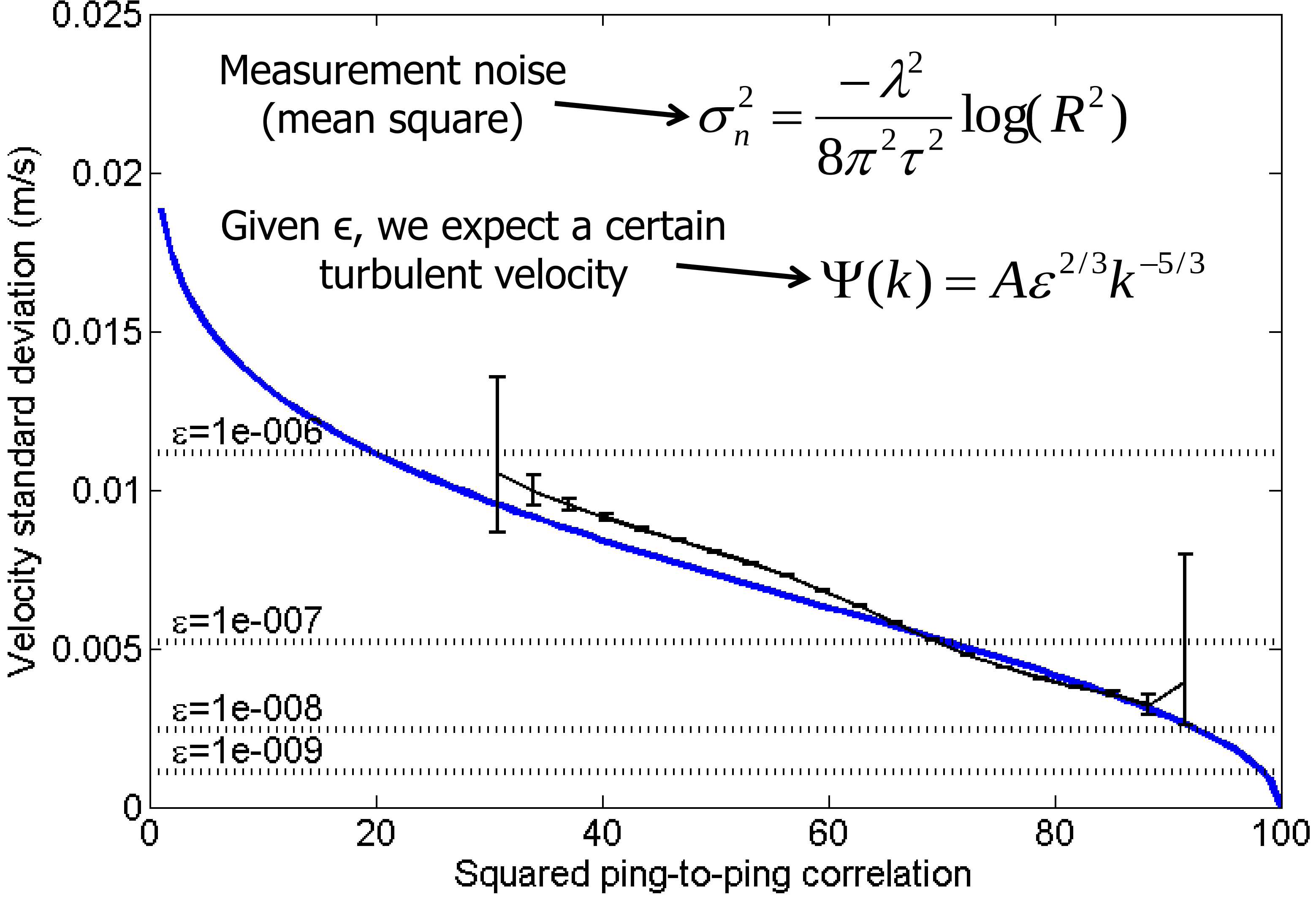
Wavenumber range chosen for fit– noise is an issue here

We can use the theoretical noise to make choices in processing



We can use the theoretical noise to make choices in processing

(Theoretical expression from Zedel et al., 1996)



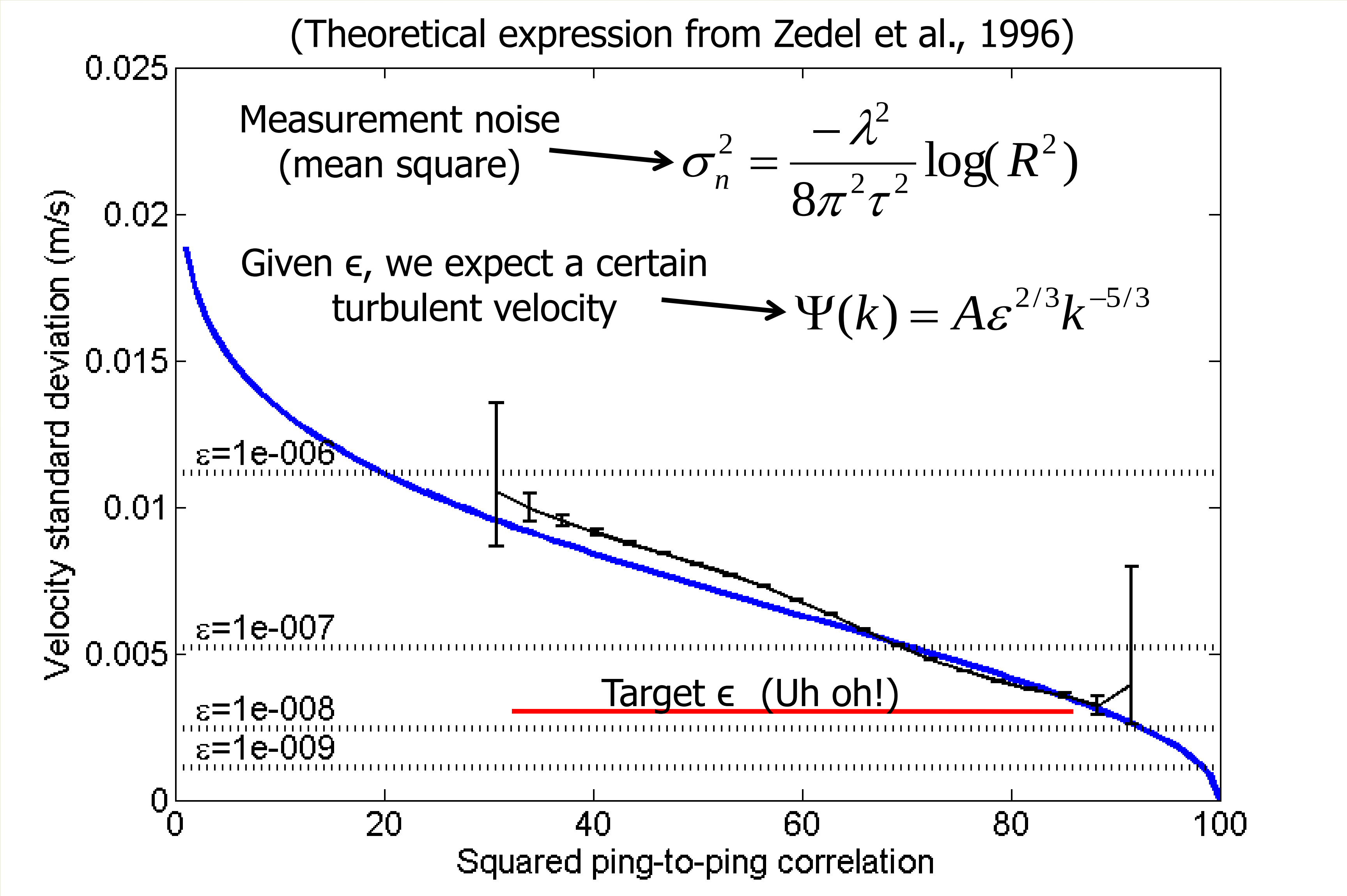
Measurement noise
(mean square) →

$$\sigma_n^2 = \frac{-\lambda^2}{8\pi^2\tau^2}\log(R^2)$$

Given ϵ, we expect a certain
turbulent velocity →

$$\Psi(k) = A\varepsilon^{2/3}k^{-5/3}$$

We can use the theoretical noise to make choices in processing



(Theoretical expression from Zedel et al., 1996)

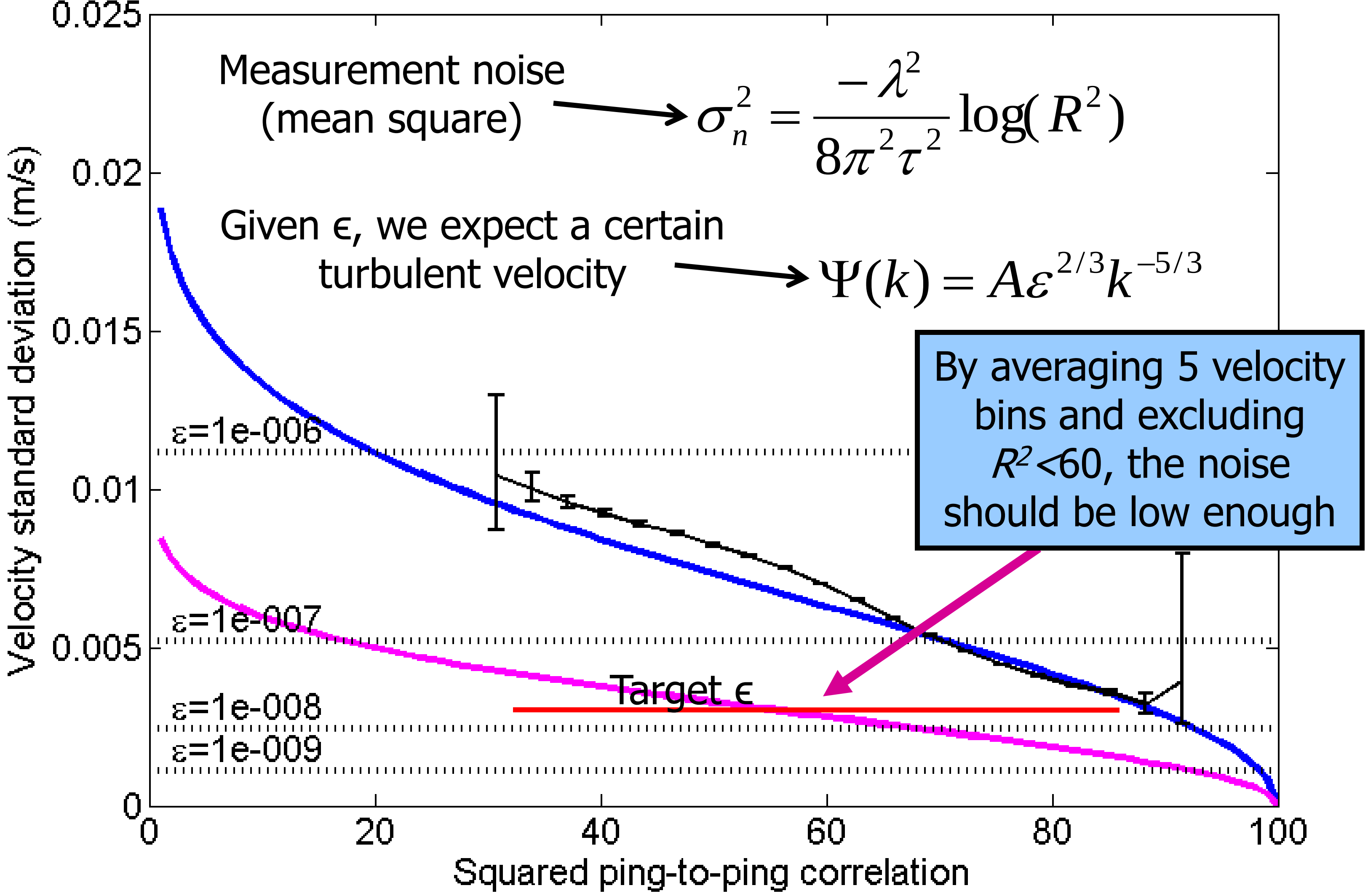
Measurement noise (mean square) → $\sigma_n^2 = \frac{-\lambda^2}{8\pi^2\tau^2}\log(R^2)$

Given ϵ, we expect a certain turbulent velocity → $\Psi(k) = A\varepsilon^{2/3}k^{-5/3}$

Target ϵ (Uh oh!)

We can use the theoretical noise to make choices in processing

(Theoretical expression from Zedel et al., 1996)



Measurement noise (mean square) →

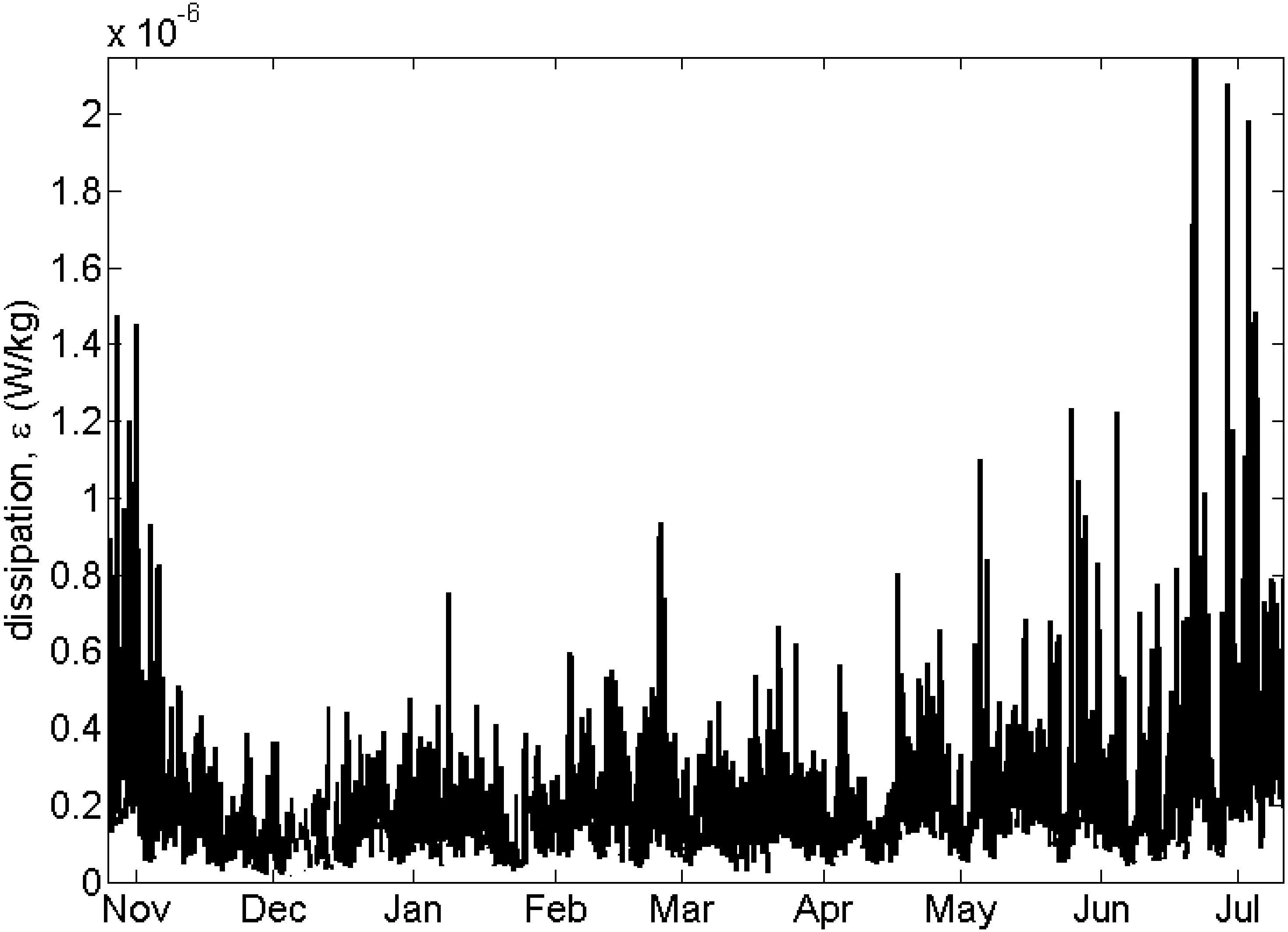
$$\sigma_n^2 = \frac{-\lambda^2}{8\pi^2\tau^2}\log(R^2)$$

Given ϵ, we expect a certain turbulent velocity →

$$\Psi(k) = A\varepsilon^{2/3}k^{-5/3}$$

By averaging 5 velocity bins and excluding R^2<60, the noise should be low enough

The result: a 9-month time series of dissipation (but, is it right?)



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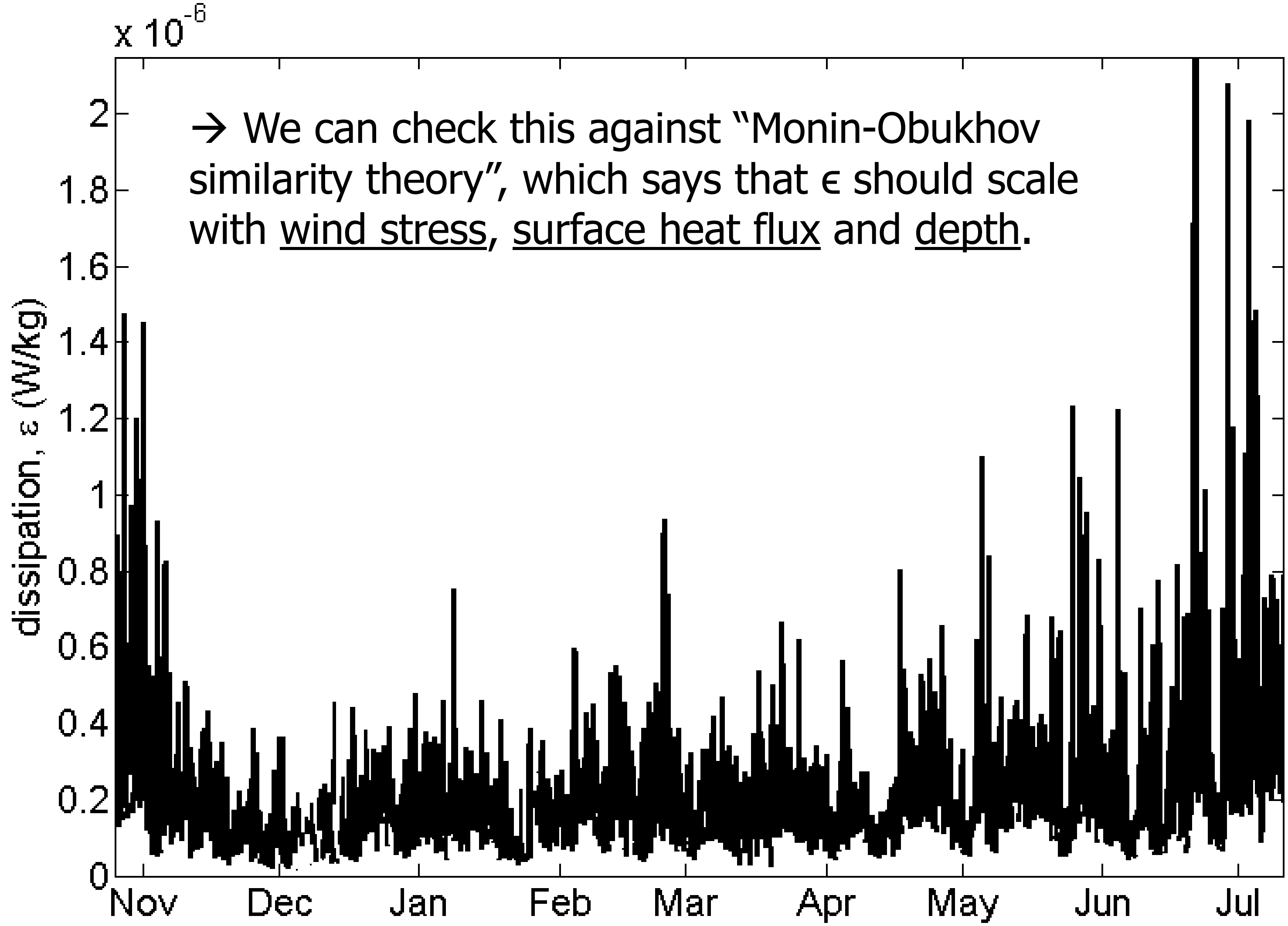
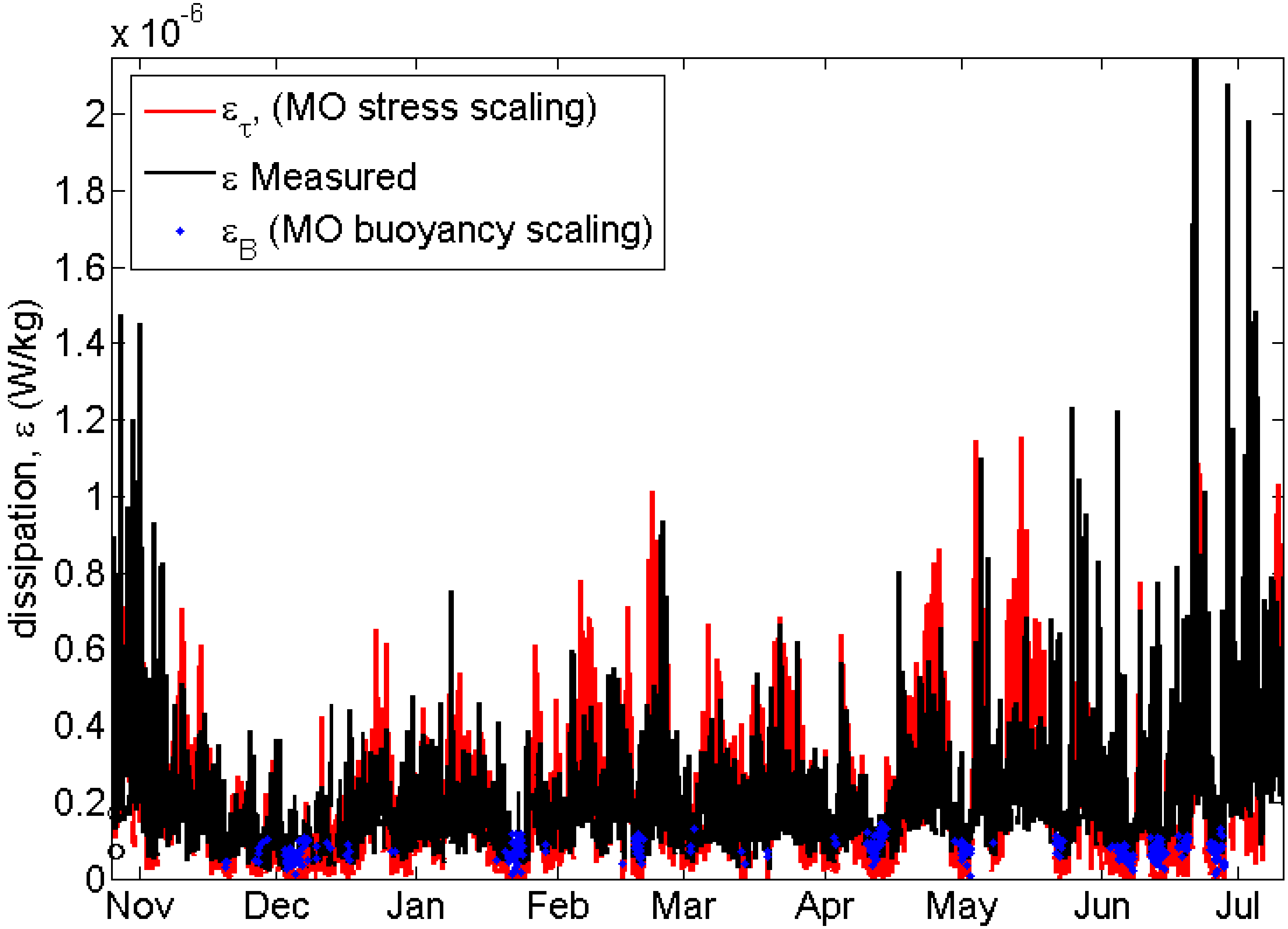
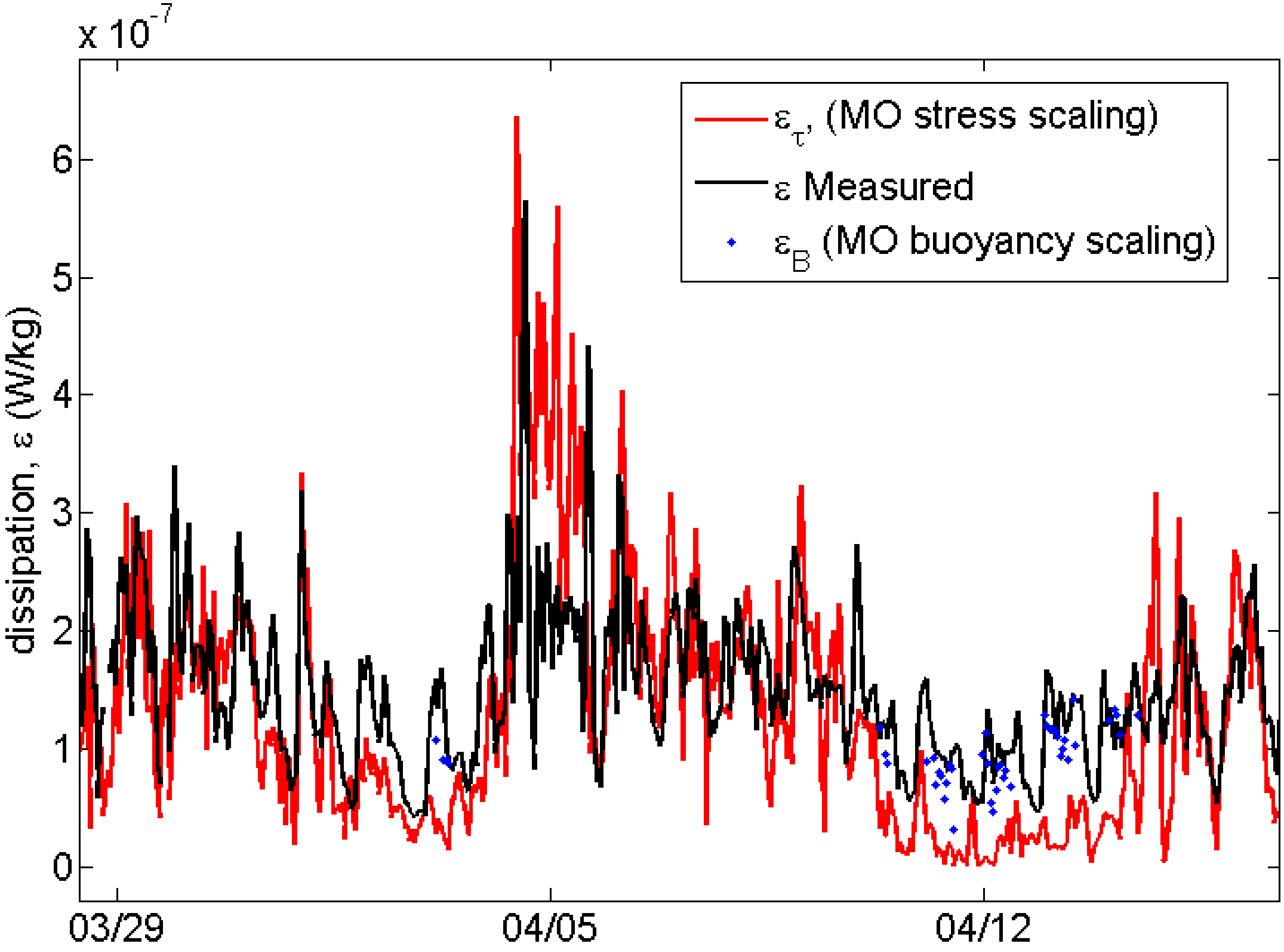


→ We can check this against "Monin-Obukhov similarity theory", which says that ϵ should scale with <u>wind stress</u>, <u>surface heat flux</u> and <u>depth</u>.

The result: a 9-month time series of dissipation
(It is looking pretty good.)



The result: a 9-month time series of dissipation
(It is looking pretty good.)



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Conclusion:

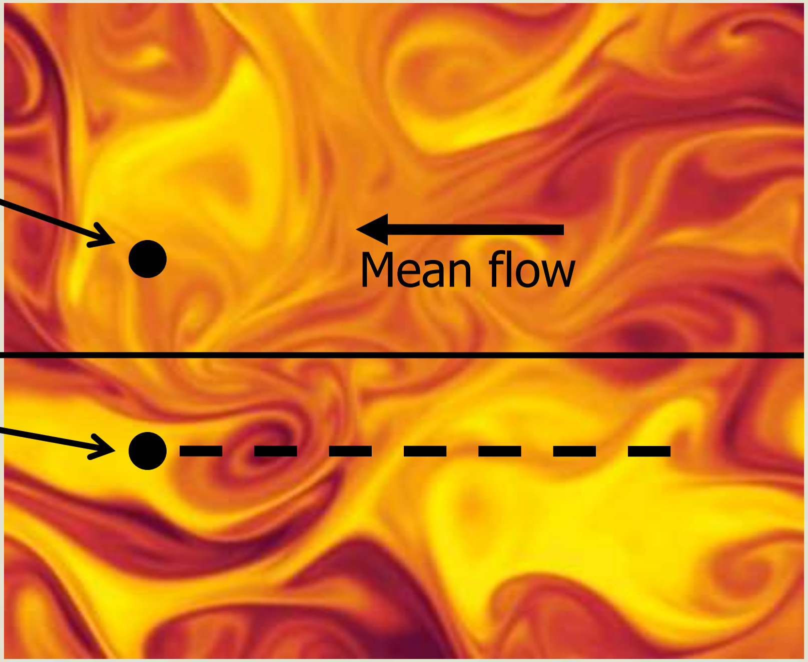
→**Aquadopp HR-Profilers appear capable of providing reasonably low-noise dissipation estimates on a moving platform, over a long time period.**

- →This will probably become increasingly true as more people use them.
- →I had to discard about 97% of the data to reach this low noise level.

→**The theoretical expression for the measurement noise as a function of measured correlation seems to hold very well.**

- →This is a very powerful result– it means we can tell the difference between physical fluctuations and noise fluctuations (in a statistical sense).

Two techniques used by the surface-wave community: The frozen-field approximation vs. Pulse-to-pulse coherent Doppler sonar



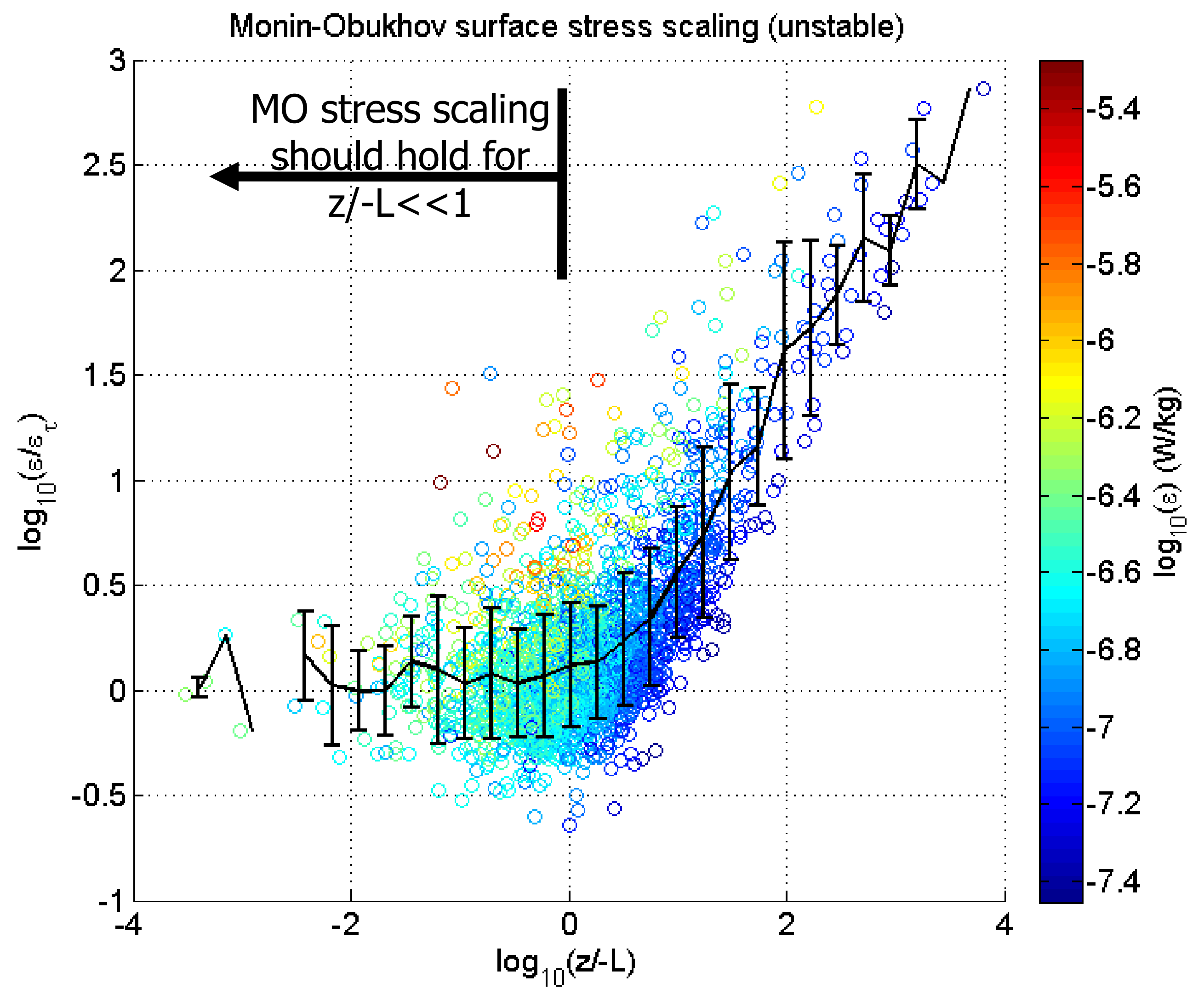
A single-point sensor has to wait ~10 sec for turbulence to be swept by (i.e., “frozen field”)

An acoustic profiler can measure a profile directly over about 1 ms

A good example using both approaches: Veron and Melville (1999)

Pulse-coherent Doppler sonar for turbulent dissipation

9 months of data (8.4 m), destabilizing surface buoyancy flux



Pulse-coherent Doppler sonar for turbulent dissipation

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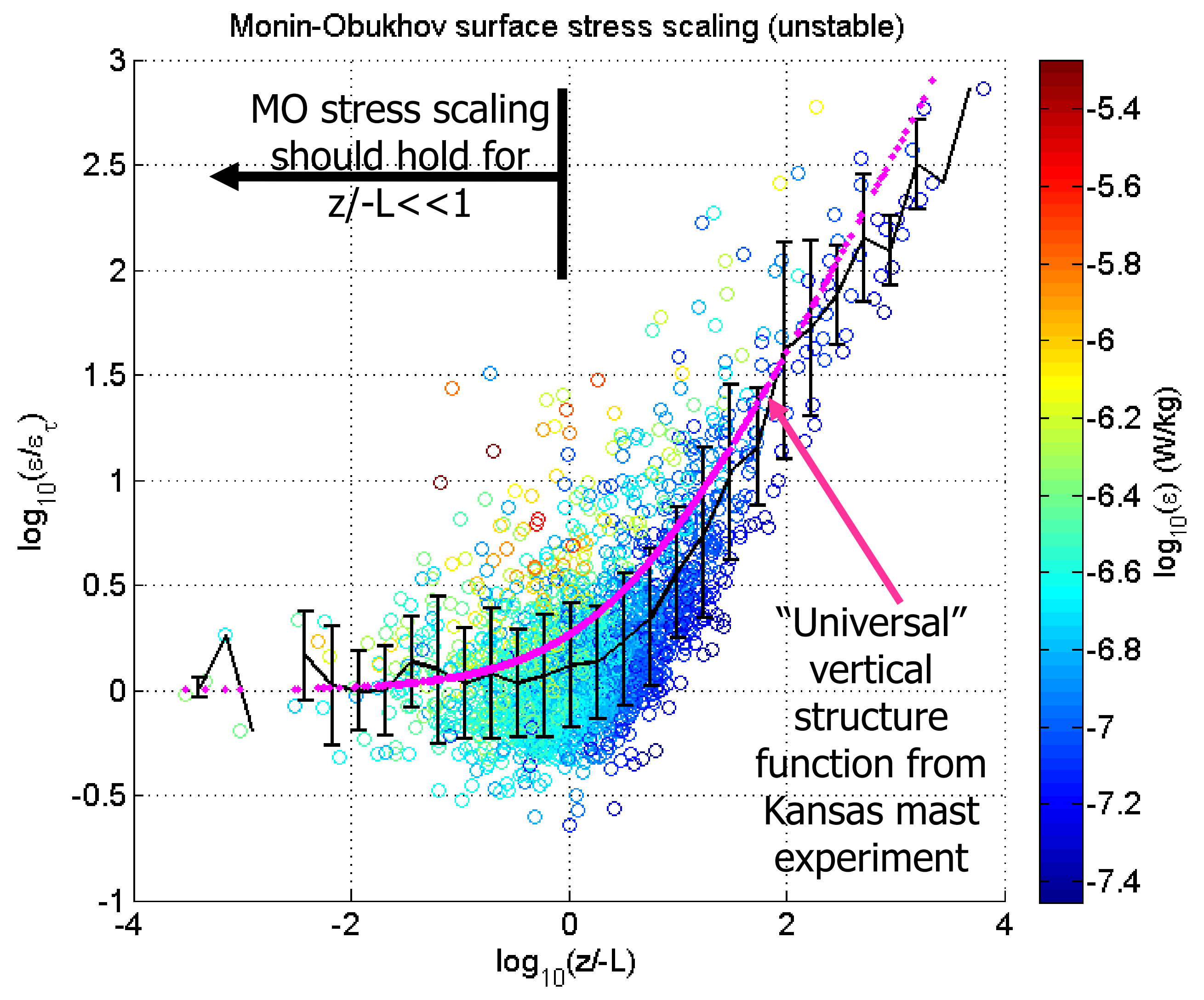
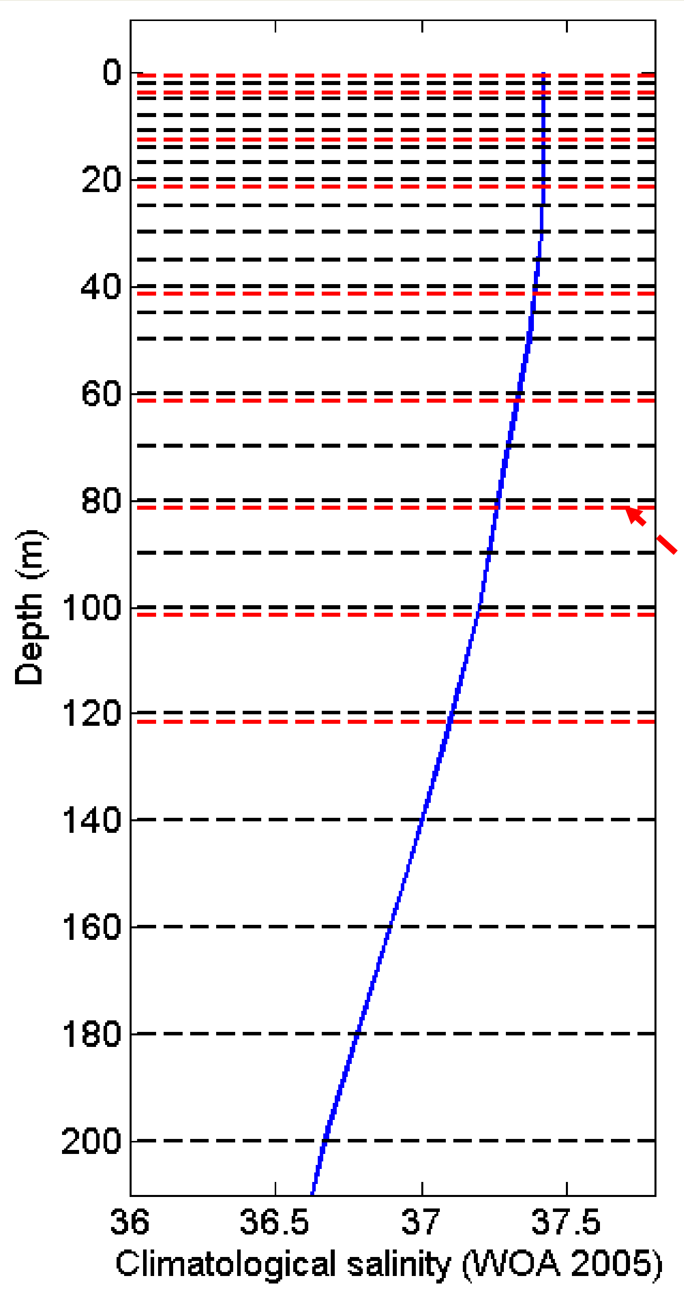


Pulse-coherent Doppler sonar for turbulent dissipation



Planned depths for pulse-coherent sonar (7 total)

→These measurements should provide temporal context for more conventional microstructure measurements in SPURS

→ They might allow useful estimates of the turbulent salt and heat fluxes

Approach:

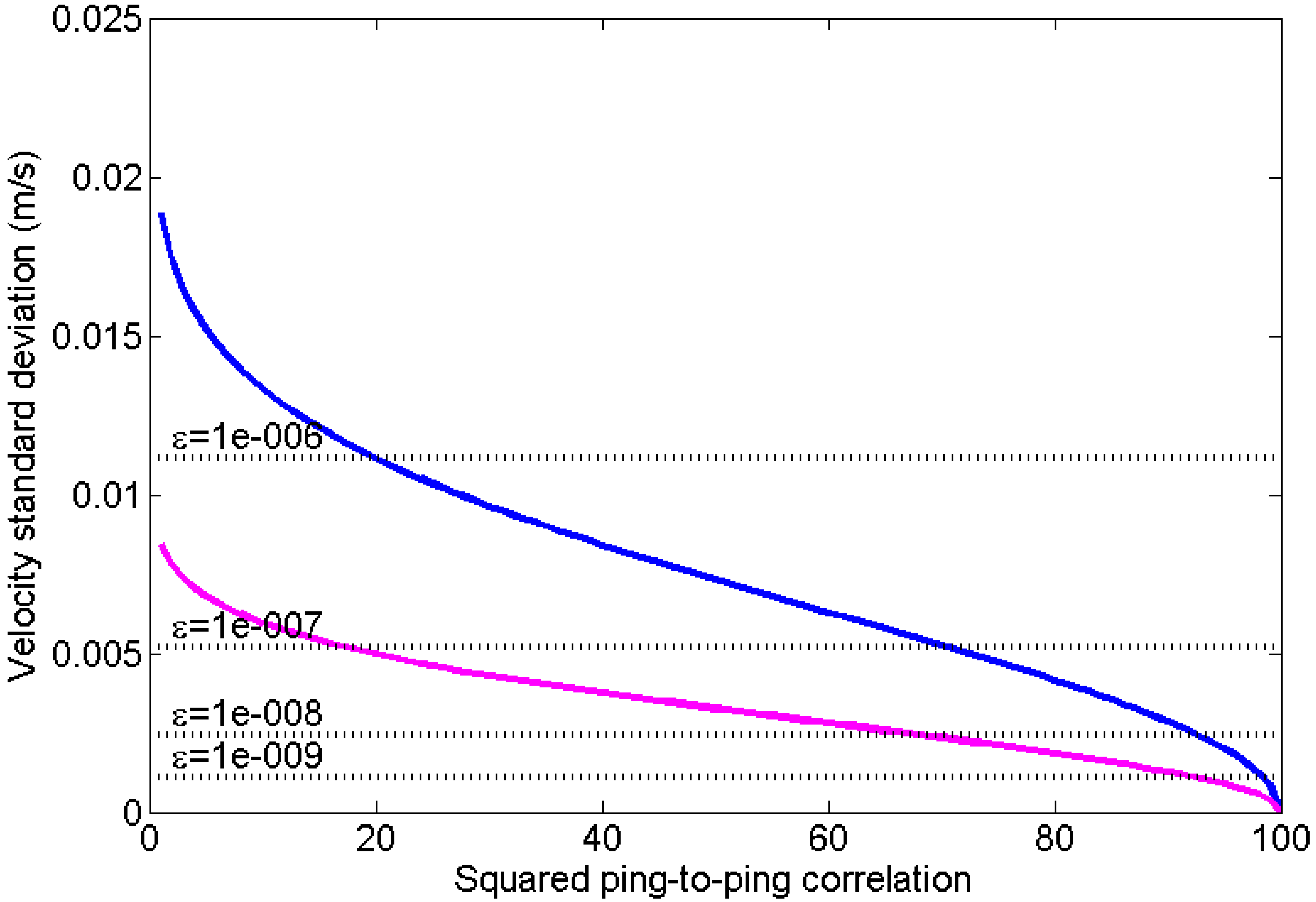
(1) Measurements of surface meteorology and radiation with dual IMET packages

(2) Enhanced SPURS IMET measurements (focus on E-P)

(3) Direct turbulent flux measurements (wind stress, latent heat flux/evap, sensible heat flux)

(4) Measurements of T, S, and U with good vertical and temporal resolution

σ_n^2 $R^2 = e^{\frac{-8\pi^2\tau^2}{\lambda^2}\sigma_n^2}$


0.025
0.02
0.015
0.01
0.005
0
Velocity standard deviation (m/s)
ε=1e-006
ε=1e-007
ε=1e-008
ε=1e-009
0
20
40
60
80
100
Squared ping-to-ping correlation

Sketch remaining slides

→D

Pulse-coherent Doppler sonar for turbulent dissipation on a surface mooring

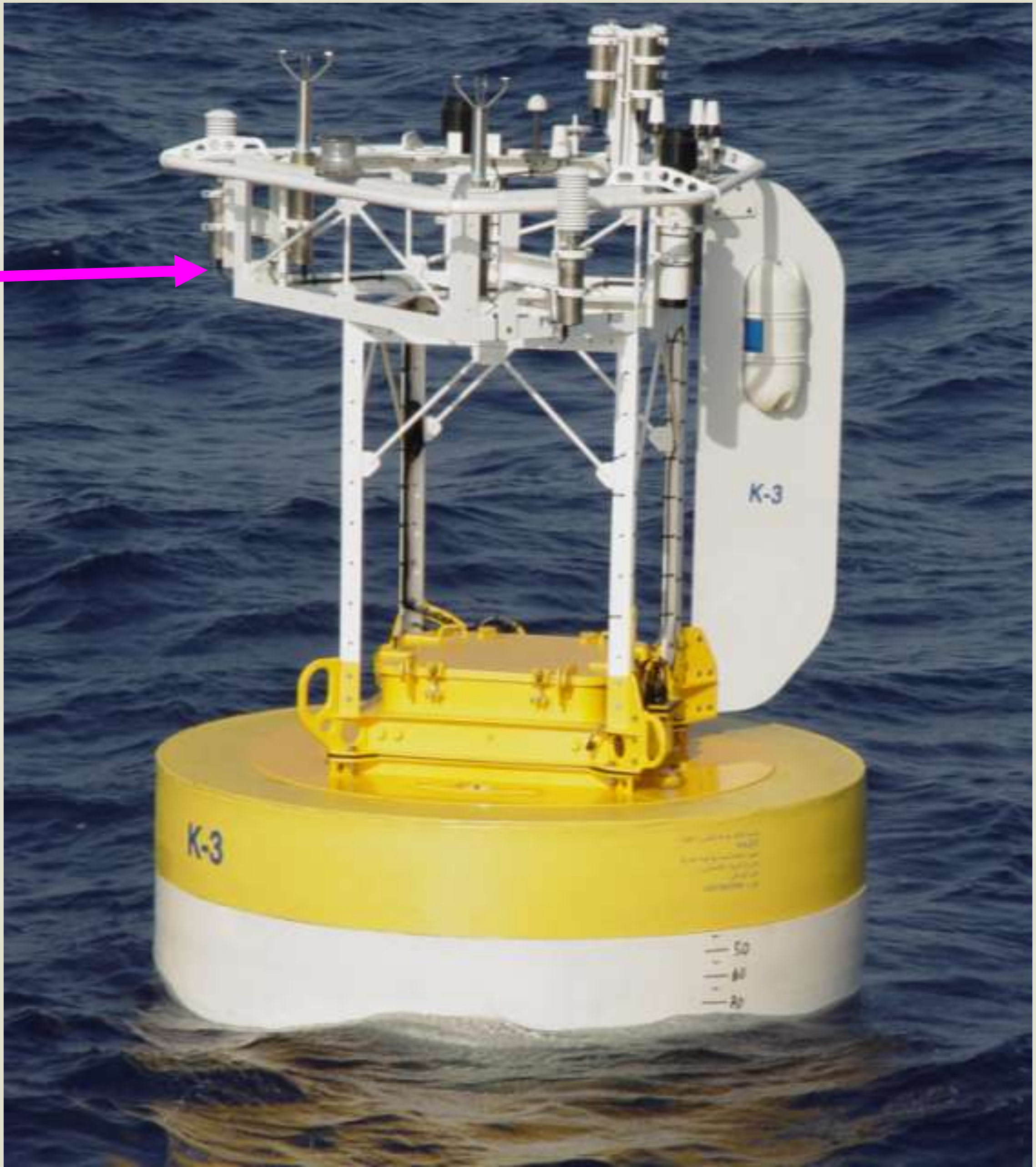
We deployed these instruments at 6 depths in the upper 100 m. 5 out of 6 instrument pairs came back looking like this.

We did get good data from an instrument pair at 8.4-m depth (above the spot where the mooring broke).

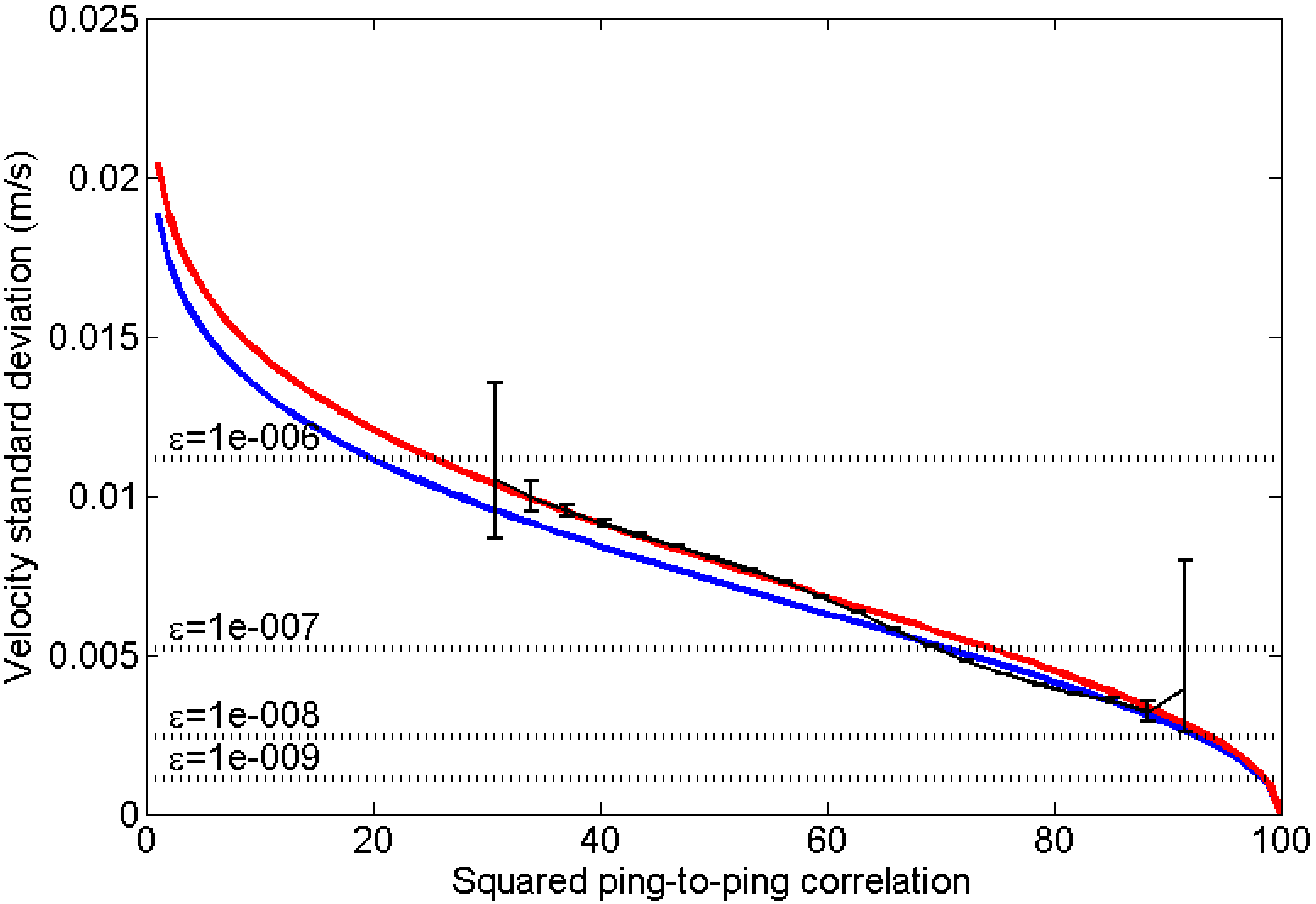
Surface buoy measurements

Shortwave and longwave radiation, air temp, humidity, winds, barometric pressure, precipitation, SST (75 cm), sea surface salinity (75 cm), surface waves

IMET Sensor Suite (Colbo and Weller, 2009; Hosom et al., 1995)



→These measurements can be used for accurate estimates of surface fluxes (wind stress, heat flux/buoyancy flux)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0.02
0.015
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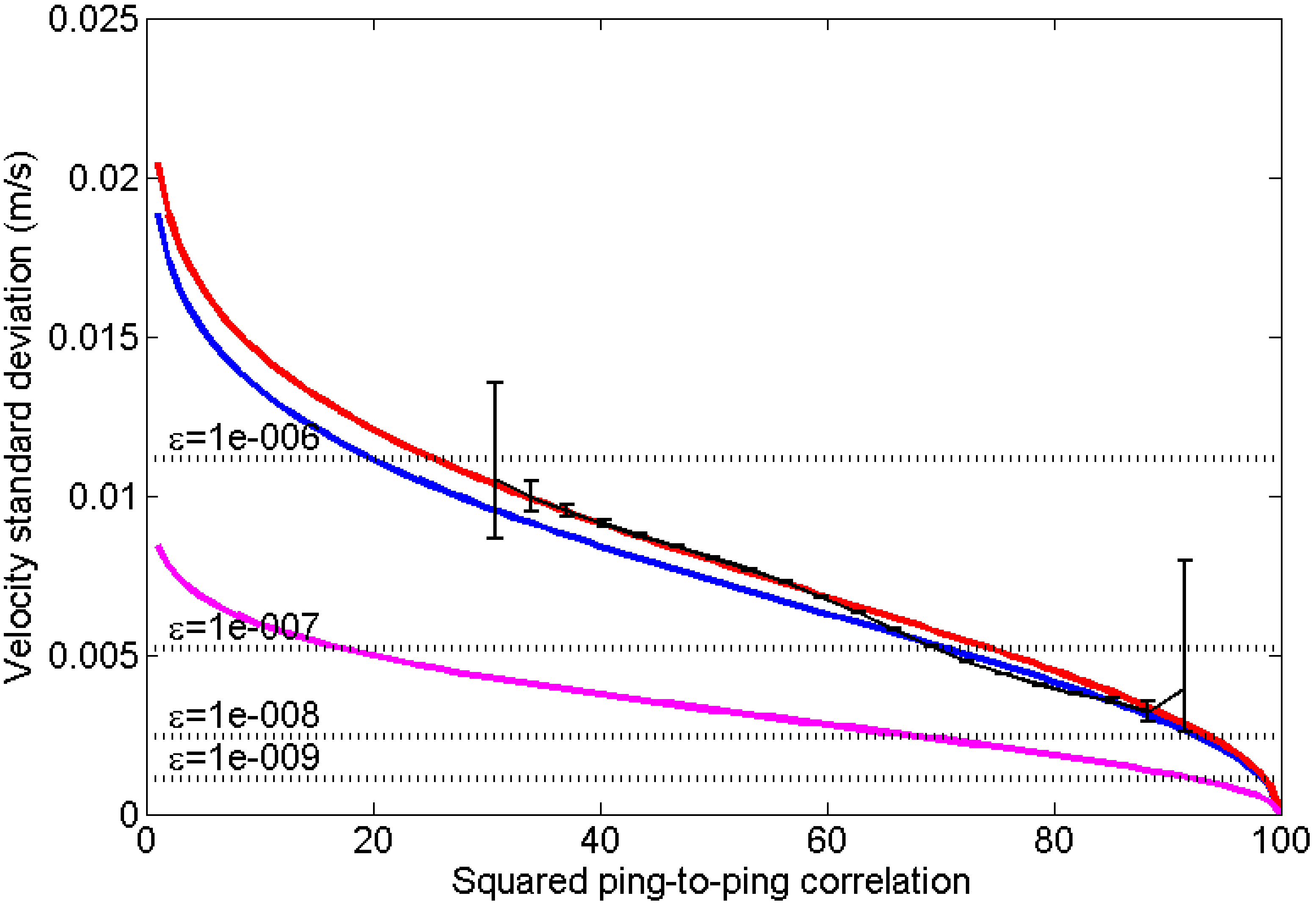
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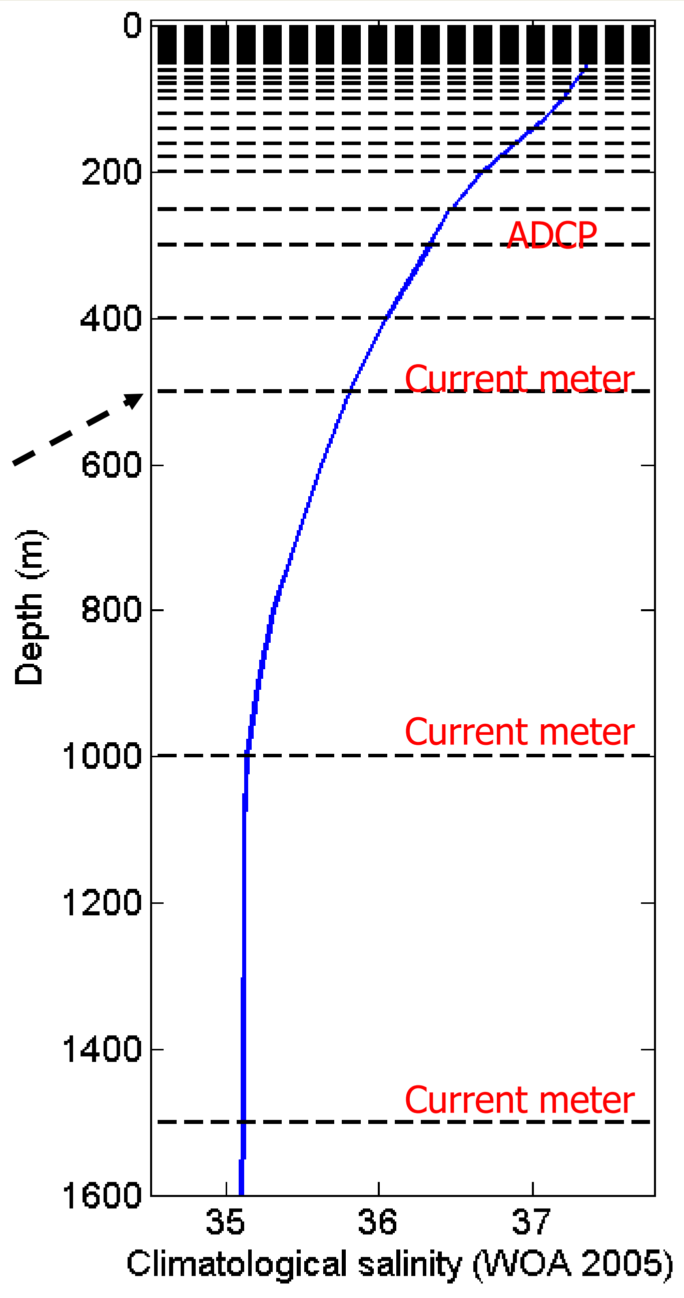
Subsurface measurements

Temperature/conductivity measurements
(SBE37s and SBE16s)
(<5 minute sampling interval)



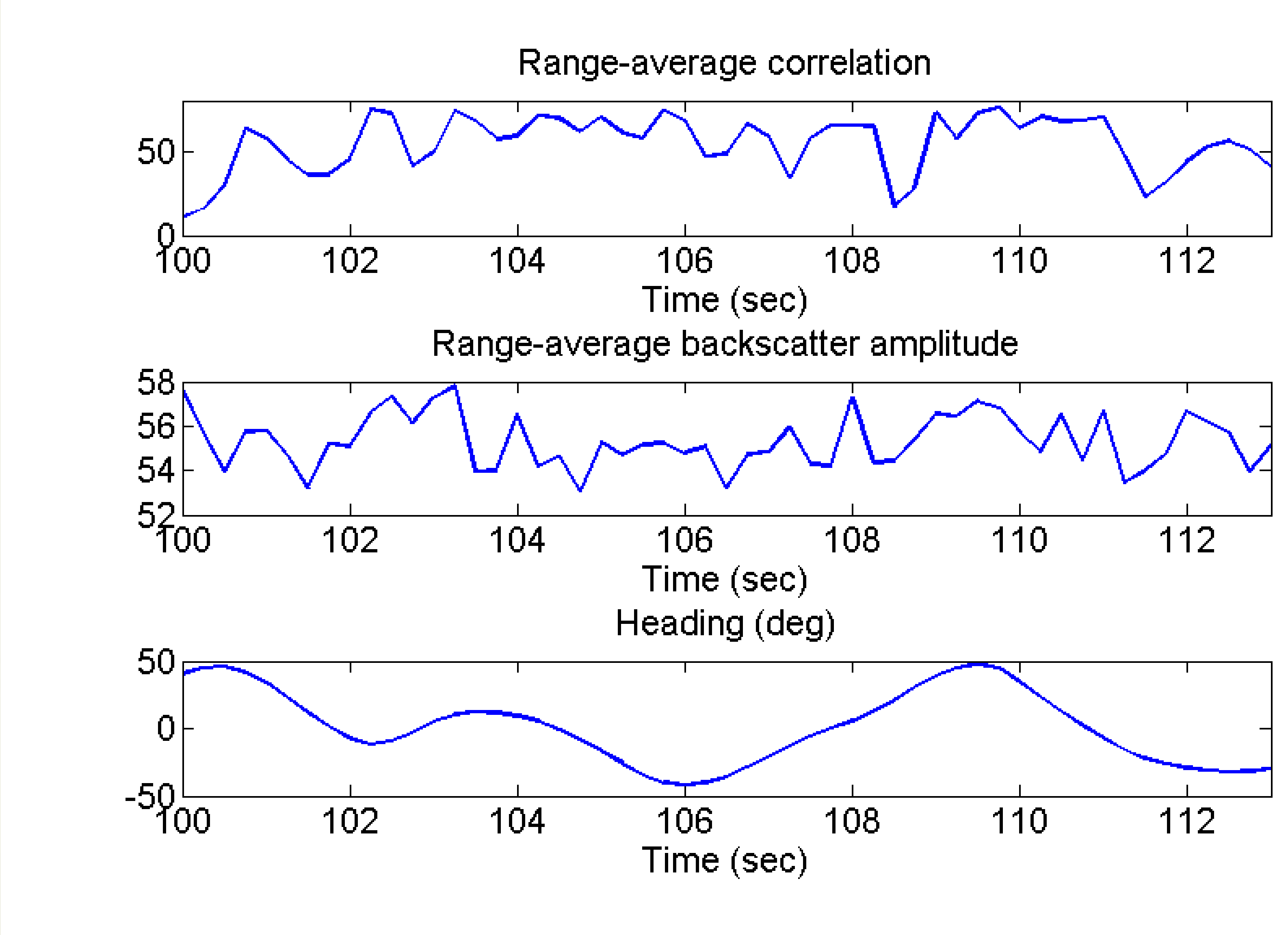
Sketch remaining slides

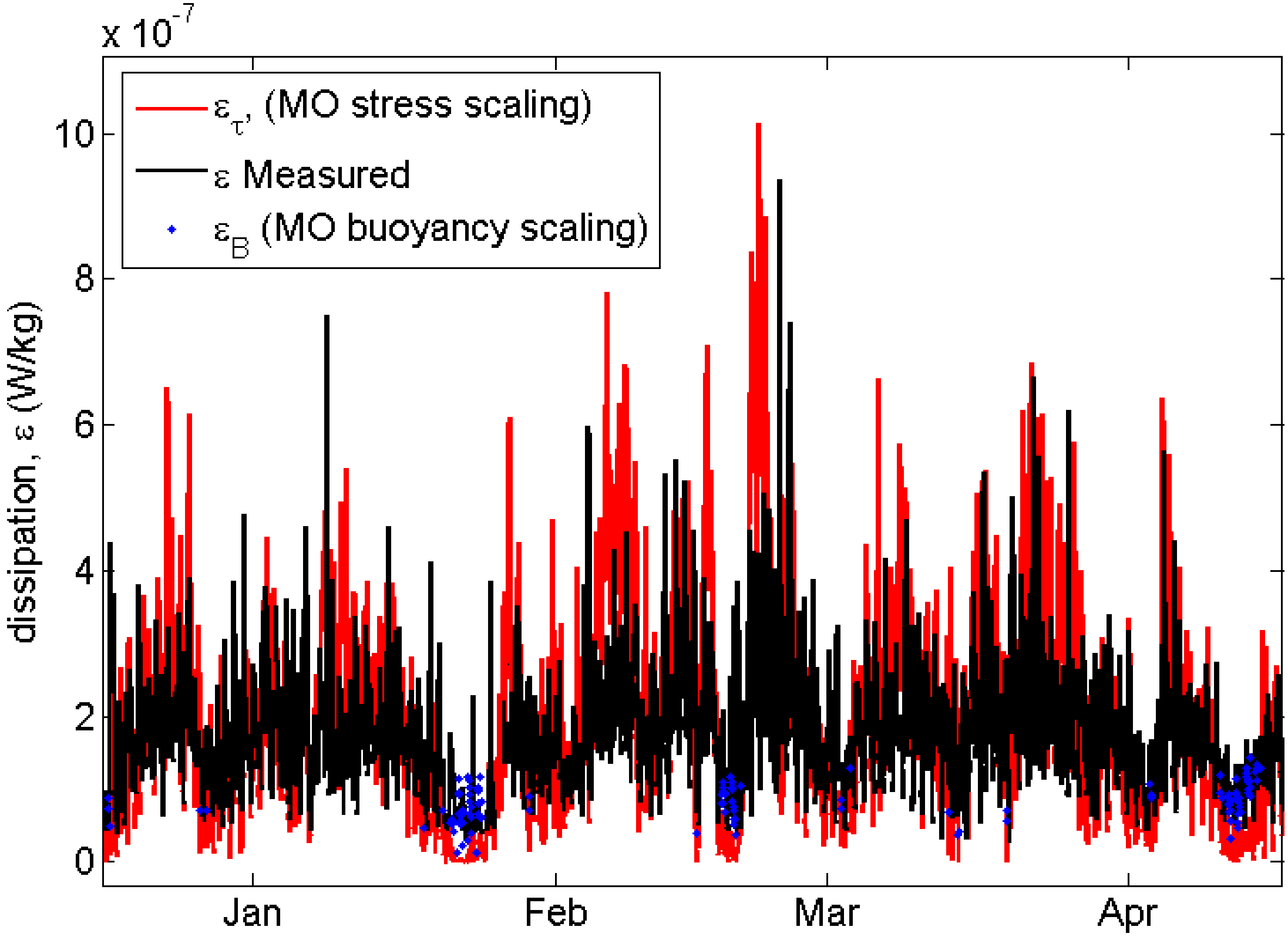
→Data example, processing (unwrap)
→Processing (noise)
→Dissipation estimates (maybe before noise?...yes)

→Example science:
    →Time series, maybe with wind, waves, and heat flux
    →Add VMP comparison
    →MO interpretation

13 seconds of data

→

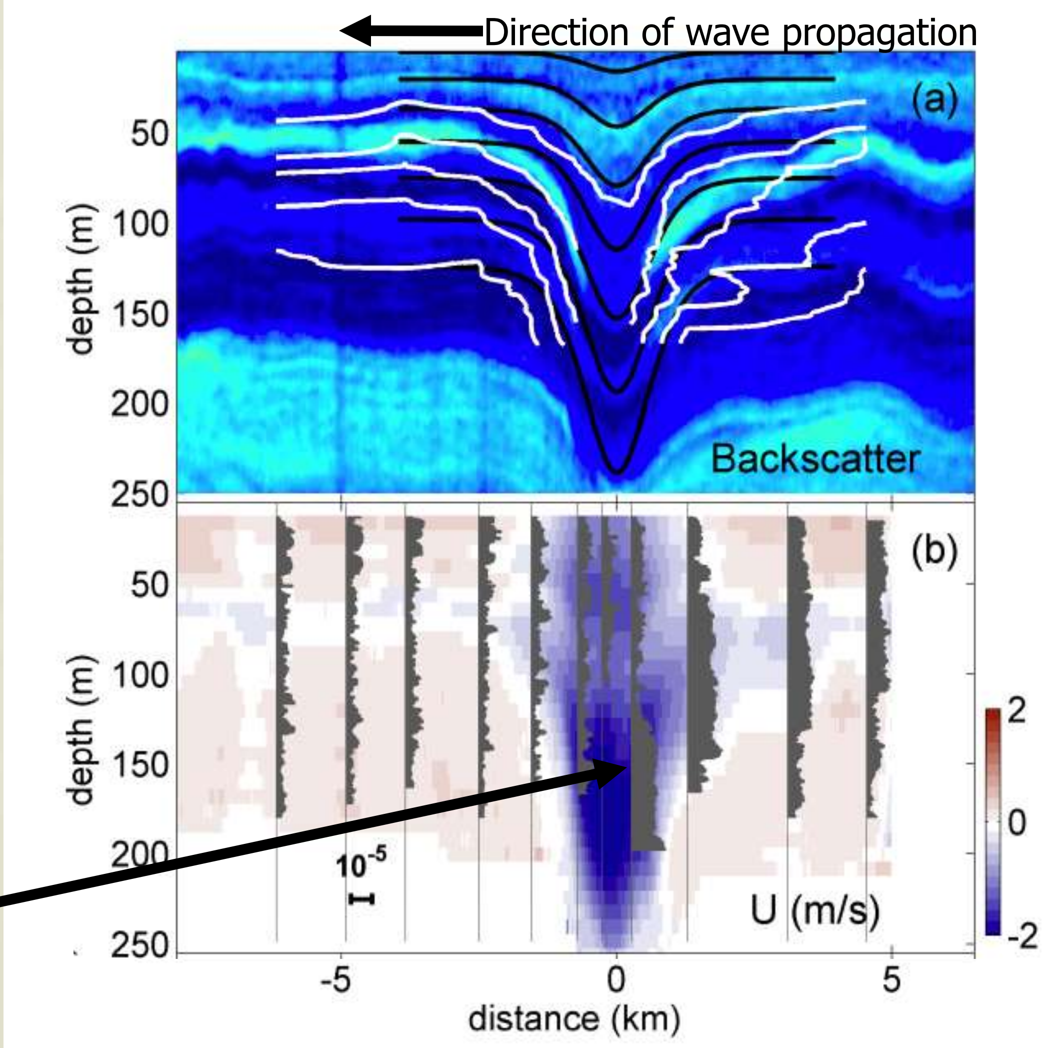



x 10^-7
10
8
6
4
2
0
dissipation, ε (W/kg)
Jan
Feb
Mar
Apr
ετ, (MO stress scaling)
ε Measured
εB (MO buoyancy scaling)

Turbulence is an important influence on the heat, momentum, and energy balances of the ocean

It is important in many phenomena:

→Example of dissipation in a large-amplitude internal wave in the South China Sea (from Lou St. Laurent, WHOI)



The very large dissipation ($\sim 10^{-4}$ W/kg) observed in and behind the wave is important to the evolution of the wave