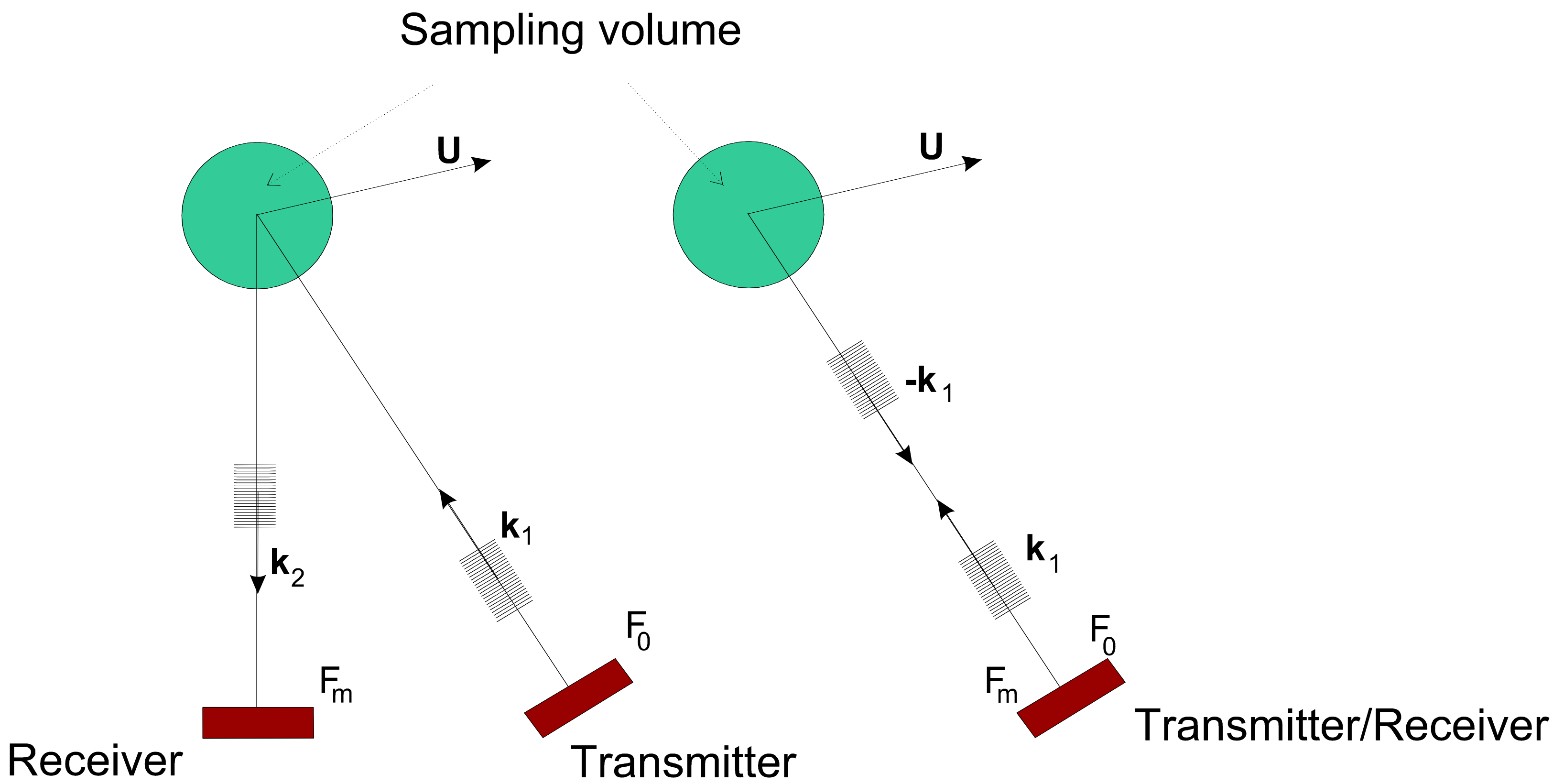
Pulse-Coherent Processing with the Aquadopp HR Profiler and Vector Velocimeter

- Why «coherent» systems?
- How do they differ?
  – And what are the practical implications?
- Applications of coherent processing
    - Turbulent flux measurements
    - Single point sensor
      – Vectrino and Vector
    - High resolution profilers

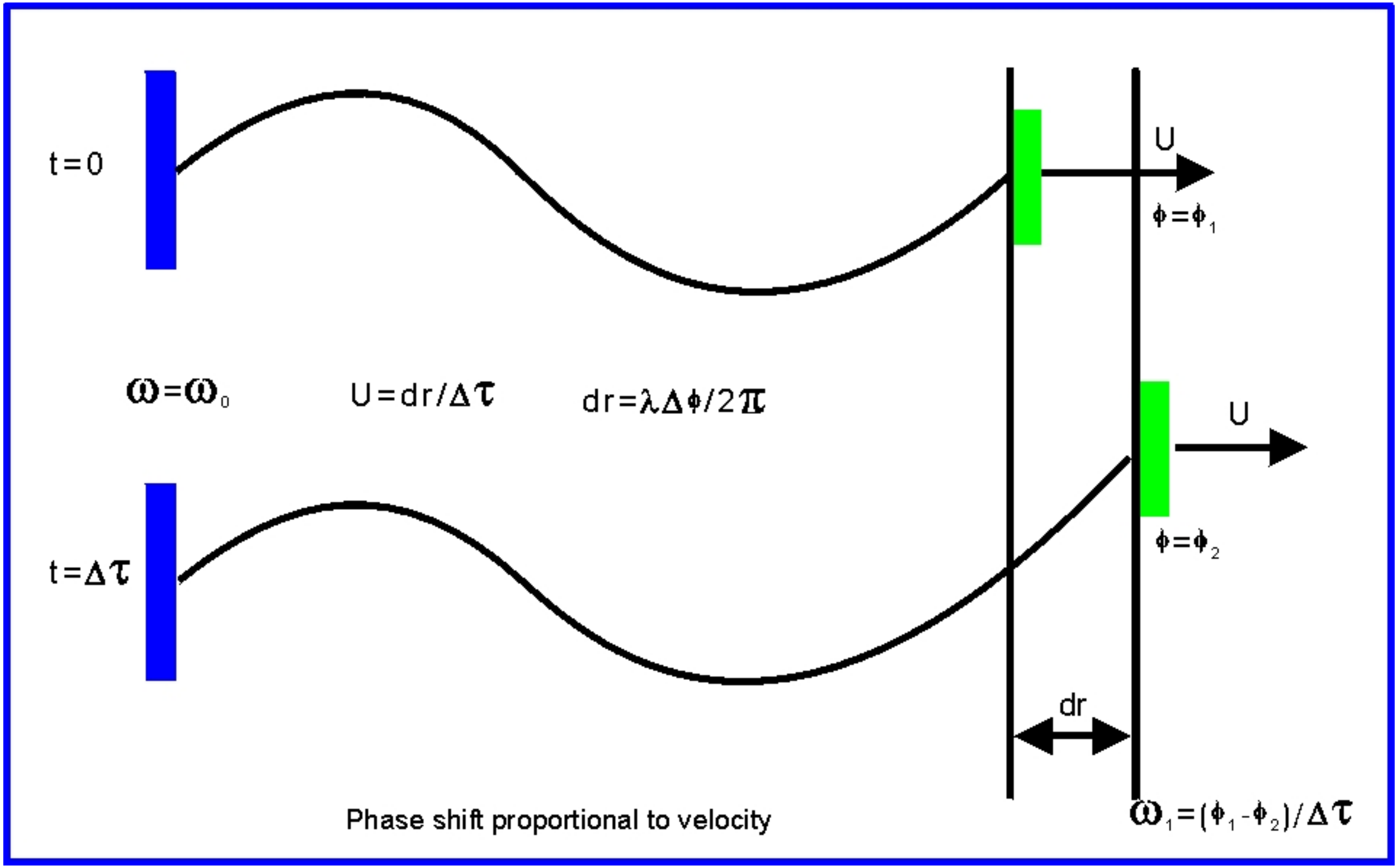
Two types of sensors



Bistatic Doppler
$(F_m = F_0 - \mathbf{k}_1\mathbf{U} + \mathbf{k}_2\mathbf{U})$

Monostatic Doppler
$(F_m = F_0 - 2\,\mathbf{k}_1\mathbf{U})$

Phase shift is measured

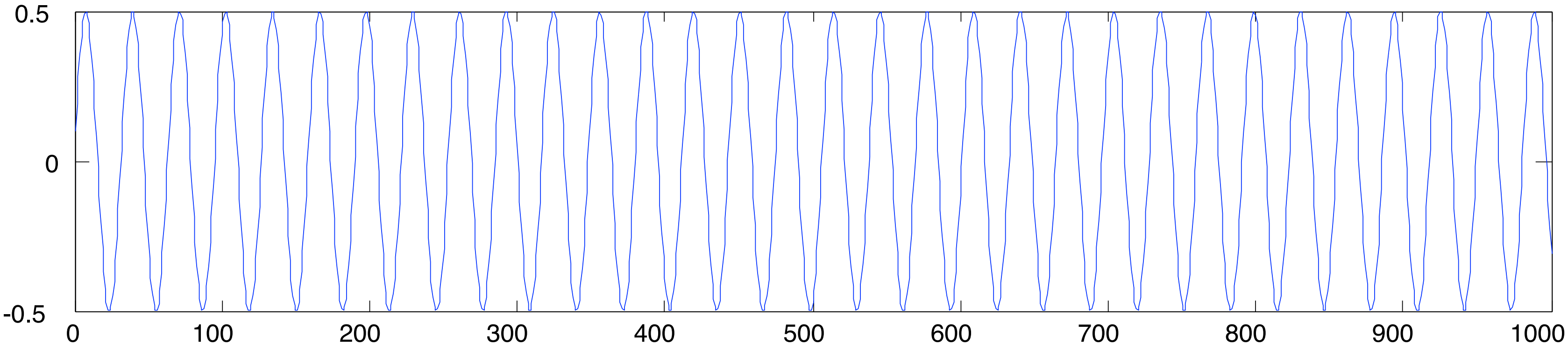


Noise level is primarily determined by processing technique

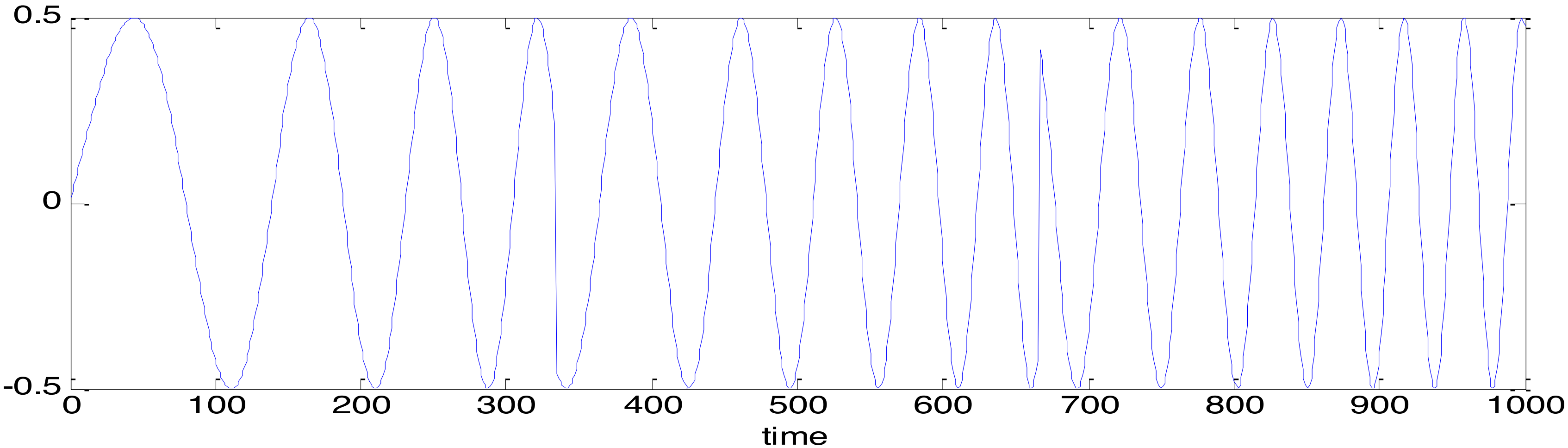
1. Single monochromatic transmit pulse (“Narrowband”)
2. Repeated, coded pulse («Broadband»)
3. Short pulses without pulse-to-pulse interference («Coherent»)

Transmit pulse defines processing technique

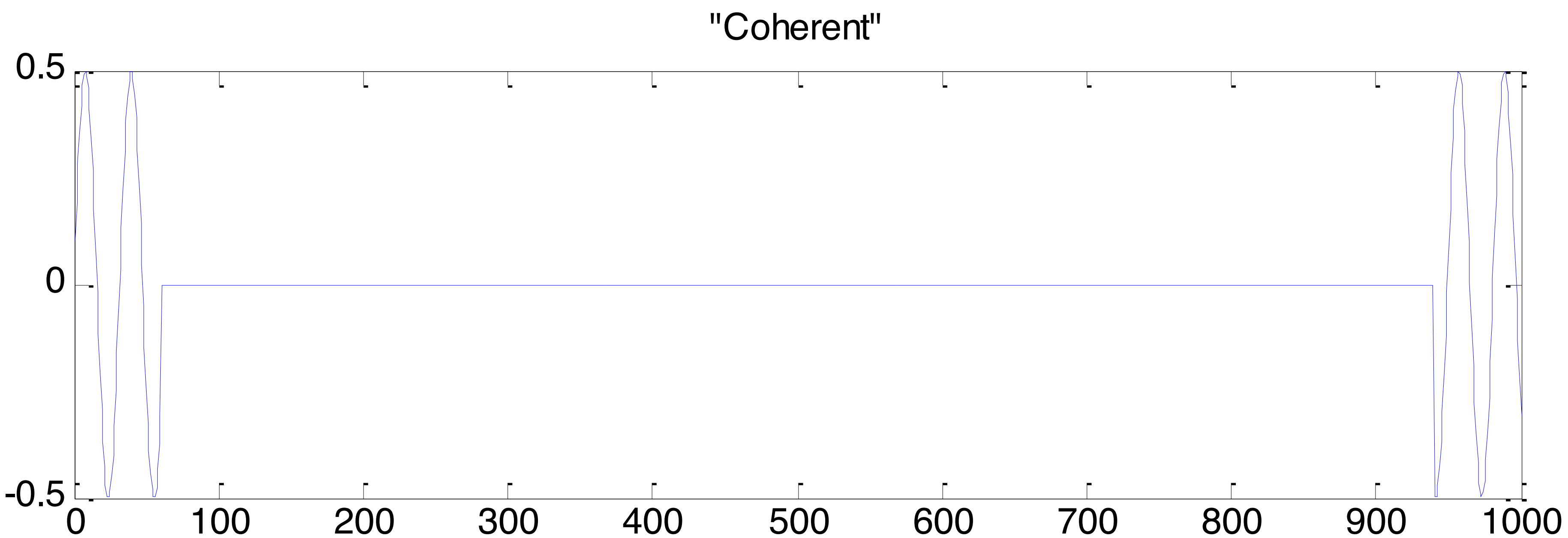
Monochromatic transmit pulse



Repeat sequence coding (chirps)



Transmit pulse with "coherent" processing



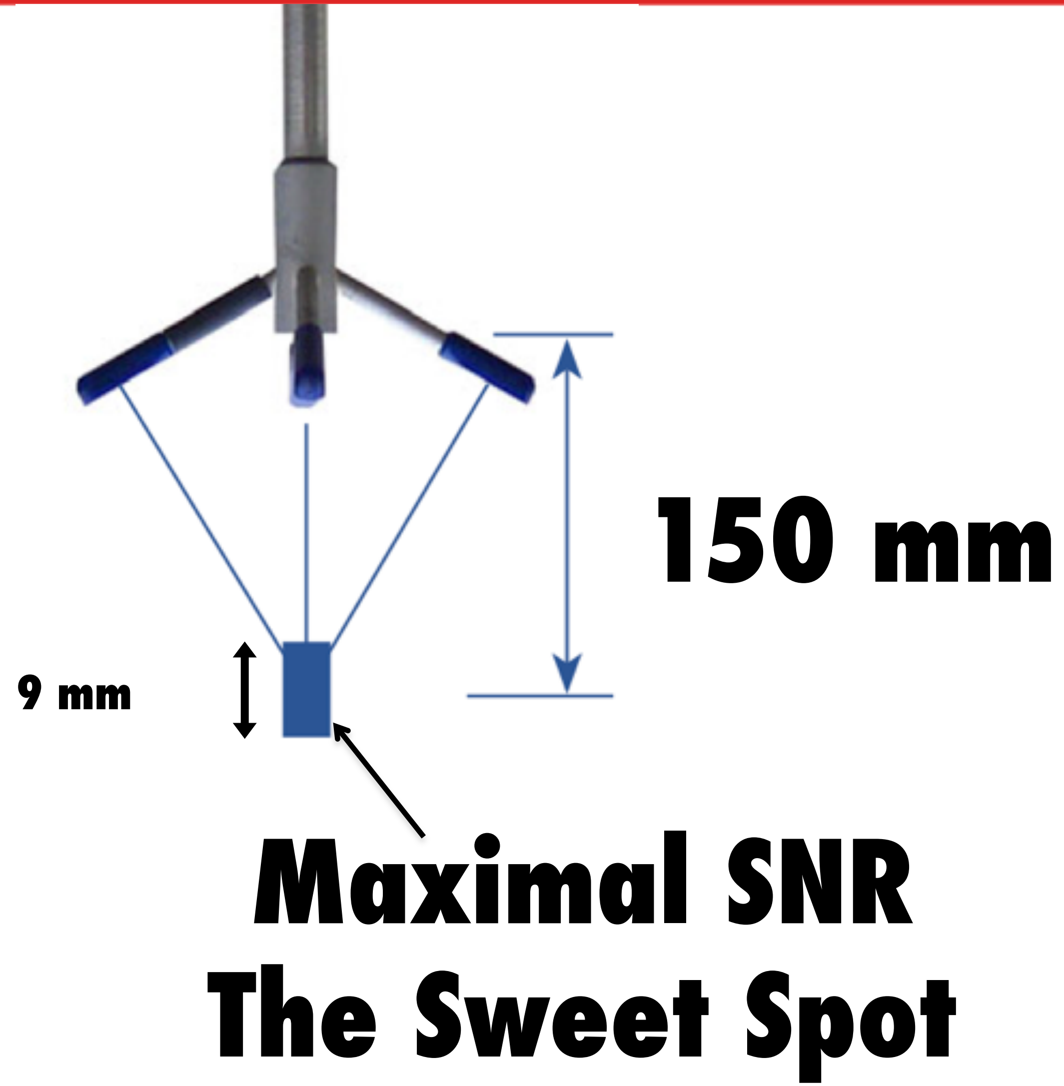
a) Distance between pulses is typically much longer than the pulse length
b) First pulse is allowed to die out before we listen to second pulse

NORTEK AS

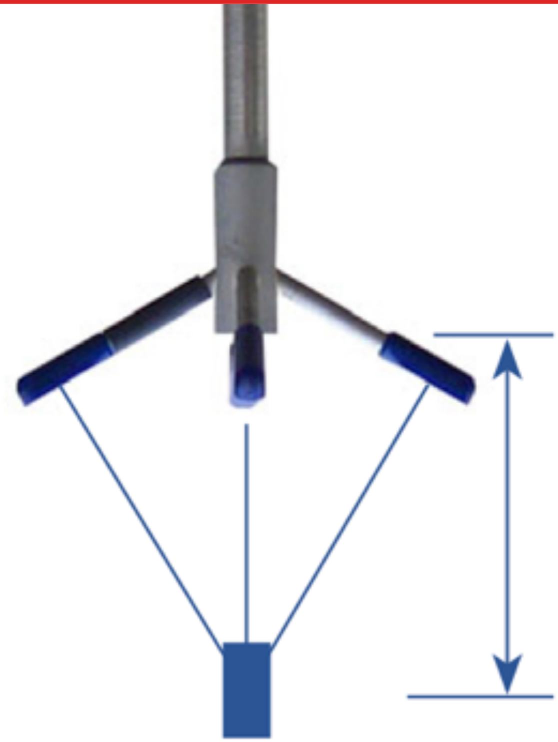
www.nortek.no

Sample Volume of a Single Point Sensor

True innovation makes a difference



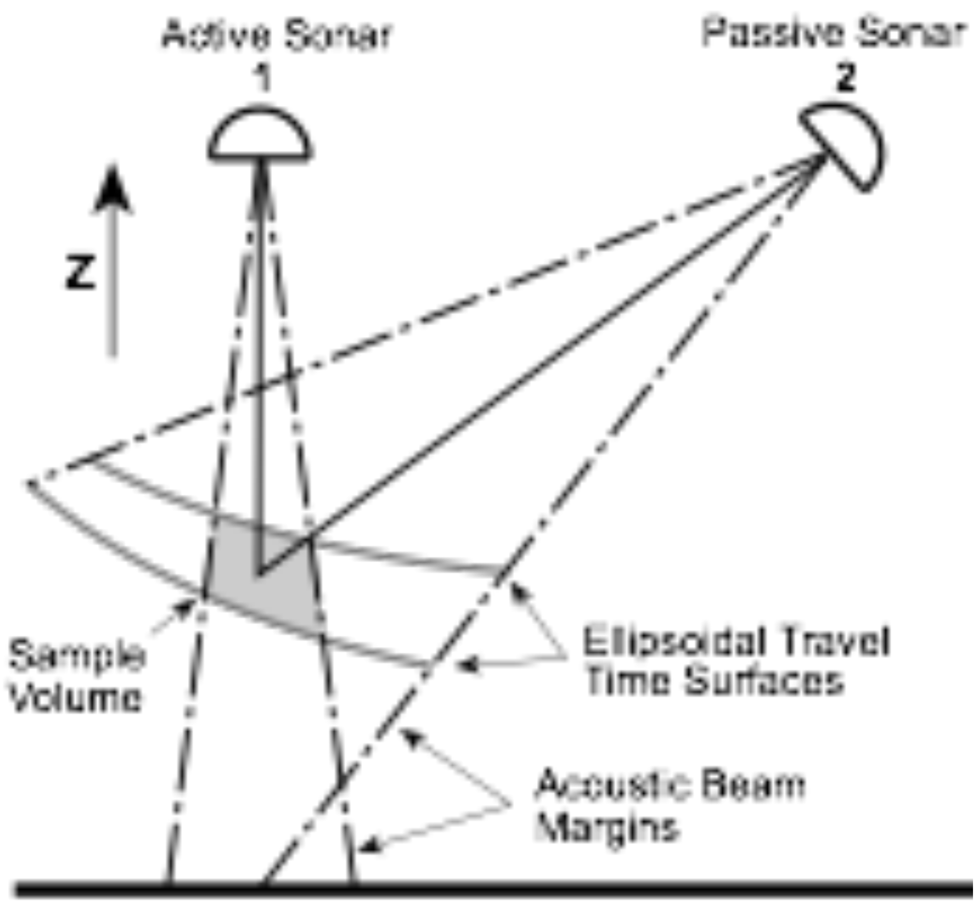
Sample Volume Shape



It's convenient to think of the sample volume as a cylinder.

However, this is a simplistic view.

Sample Volume Shape

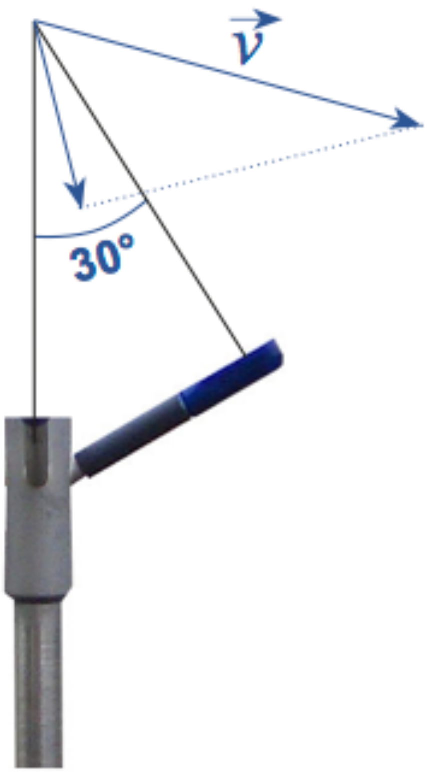


The intersecting beam patterns define two of the sample volume dimensions.

Range gating defines the third dimension.

Zedel, L. (2002). A three-component bistatic coherent Doppler velocity profiler: error sensitivity and system accuracy. Oceanic Engineering.

Velocity Measurement



- Scattering material in the water reflects acoustic pulses.
- Movement of the scatterers **relative** to the transmitter and receiver results in a Doppler shift.
- The Vector uses the shift to estimate velocities using the Doppler relationship.

$$\boxed{\Delta f} = \frac{2f}{c}\boxed{V_{rel}}$$

What the Vector measures **What the Vector calculates**

Output Data

Velocities – output in either *beam* or *XYZ* coordinate systems in m/s.

Amplitude – measure of the return signal strength in digital counts or dB relative to the transmit strength.

Signal-to-Noise ratio (SNR) – exactly that, expresses **Amplitude** relative to the instrument noise level in dB. Higher is better.

Correlation – a measure of signal quality in percent. Higher is better.

All data is output at the user specified sample rate (1-100 Hz)

Pulse Coherent Processing

- The Doppler shift (**Δ***f*) is estimated from a change in phase (**Δϕ**)between two signals.
- Basic operation is ping-listen-ping-listen. There is expected to be one pulse in the water at any time in the sample volume.
- This method produces high spatial resolution, low noise data.
- There are tradeoffs between maximum velocity, profile range and sample rate.

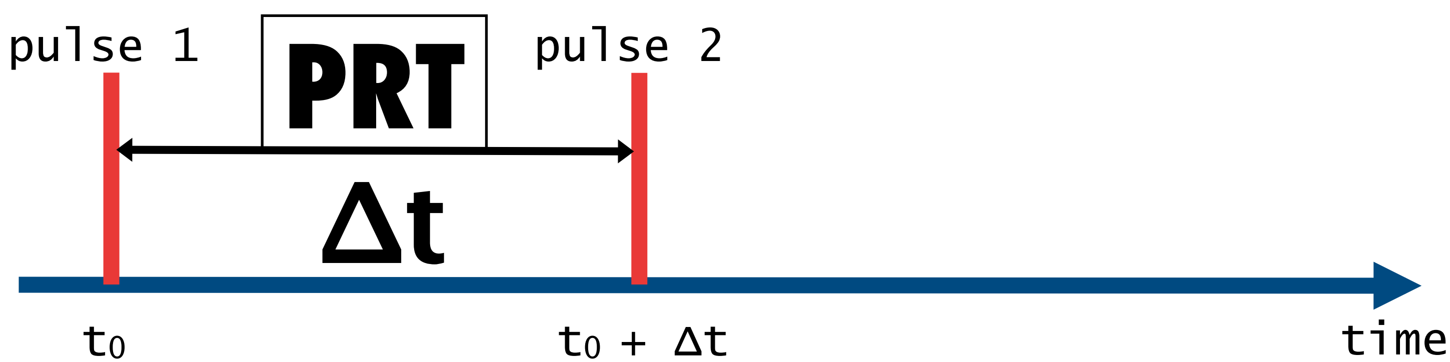
Lhermitte, R., & Serafin, R. (1984). Pulse-to-pulse coherent Doppler sonar signal processing techniques. Journal Of Atmospheric And Oceanic Technology, 1(4), 293-208.

Pulse Coherent Processing - Terminology

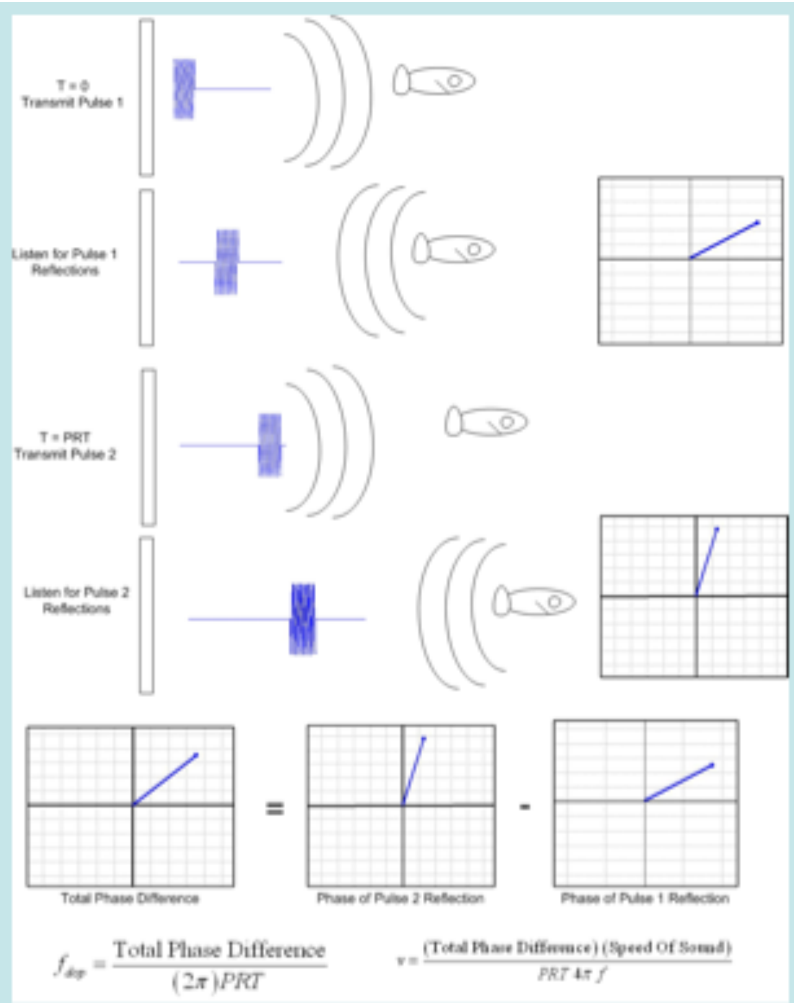
Pulse repetition time (PRT) - the time between pulse 1 and pulse 2 transmission, also called the **pulse repetition frequency (PRF)**, **distance**, or **lag**.

Δφ - the change in phase between pulse 1 and pulse 2.

$$f_{pr} = \frac{1}{PRT}$$



Pulse Coherent Processing - Basic Sampling



t=0, transmit pulse 1

t>0, t<Δt, listen to pulse 1

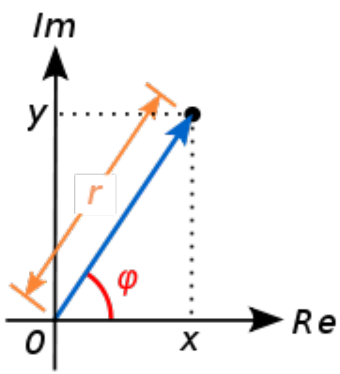
t=Δt, transmit pulse 2

t>Δt, t<2Δt, listen to pulse 2

The received signals are expressed as complex numbers (an in phase and quadrature component), making it relatively simple to calculate Δϕ.

Repeat…

Pulse Coherent Processing - Phase Determination



$\Delta\phi$ is calculated as $\phi_2 - \phi_1$ with ϕ_i the argument (`atan2()` in most programming languages) of the complex signal representation.

$$v = \frac{c\Delta\phi}{4\pi f \Delta t}$$

$\Delta\phi$ is used in the Doppler relationship to calculate velocity. $\Delta\phi/(2\pi\Delta t)$ is the Doppler shift.

f **is the carrier frequency (6 MHz)**
c **is speed of sound**

Ambiguity Velocity

$$v = \frac{c\Delta\phi}{4\pi f \Delta t}$$

$$v_{max} = \frac{f_{pr}\lambda}{4}$$

$$\lambda = \frac{c}{f}$$

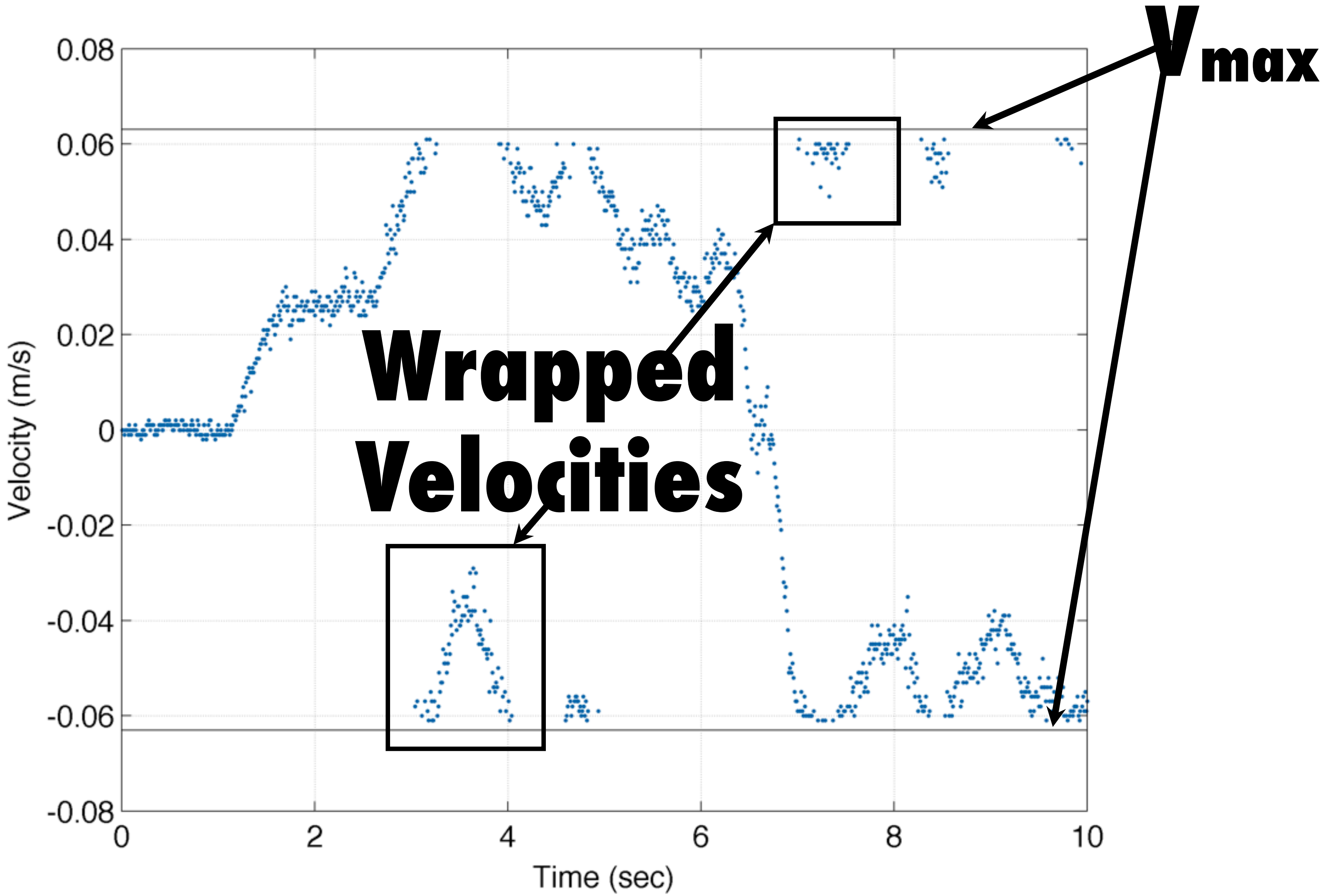
$$v_{max} = \frac{c}{4f\Delta t}$$

ϕ (and **Δϕ**) is unambiguously defined for ±π

This leads to a maximum measurable velocity, $\mathbf{V_{max}}$.

Velocities greater than $\mathbf{V_{max}}$ lead to phase wrapping.

Phase Wrapping

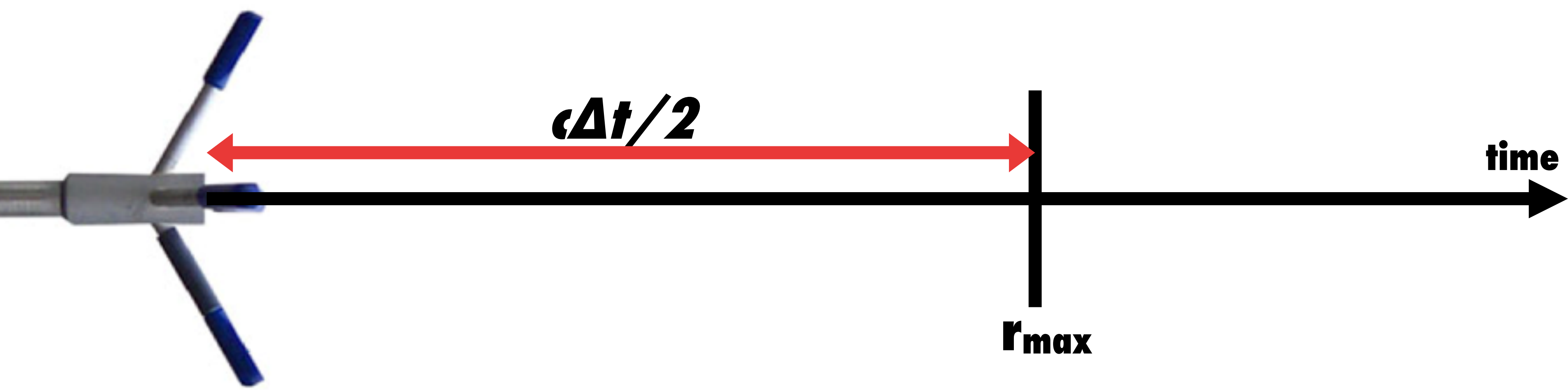


Ambiguity Range

There is an unambiguous range, r_{max}, for pulse coherent operation.

$$r_{max} = \frac{c}{2 f_{pr}}$$

$$r_{max} = \frac{c\Delta t}{2}$$



Velocity-Range Ambiguity Product

Combining the velocity and range ambiguity expressions, we obtain the velocity-range ambiguity function.

$$r_{max} v_{max} = \frac{c\lambda}{8}$$

Interpret this as the beam velocity times the range should not exceed this value.

With c=1500 m/s, for a 10 MHz system this is ~0.03 m^2/s.

Limits on Ambiguity

- The Vector needs to process the return signals.
- The **Pulse Repetition Time** can not be made arbitrarily small for many reasons.
- There is a tradeoff between velocity and range.
  - Limitations of the electronics actually constrain $\mathbf{V_{max}}$
  - Probe geometry actually constrains $\mathbf{r_{max}}$

Ensemble Sampling

With c=1500 m/s, it takes approximately 3 μs for a pulse to cover the Vector profile range (there and back).

User sample interval is a maximum of 0.02 sec, 200 times slower than the maximum ping rate.

Multiple ping pairs are ensemble averaged to improve statistics.

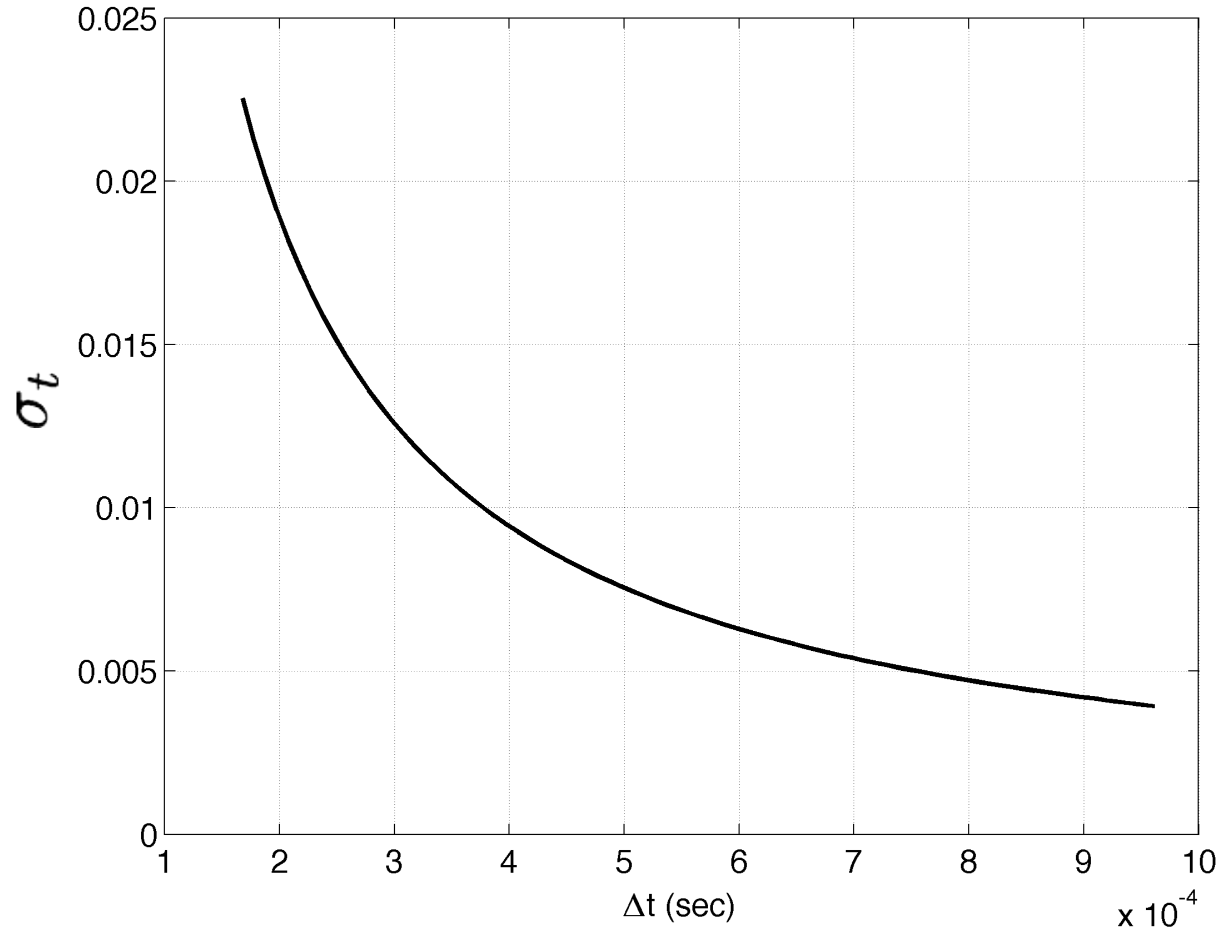
The reduction in variance is proportional to the number of averaged ping pairs.

Setting the **Velocity Range** appropriately is the most important step to achieving good data quality.

Noise versus Δt

As **Velocity Range** increases (**Δt** decreases), there is an increase in variance due to noise.

Choose your Velocity Range wisely.



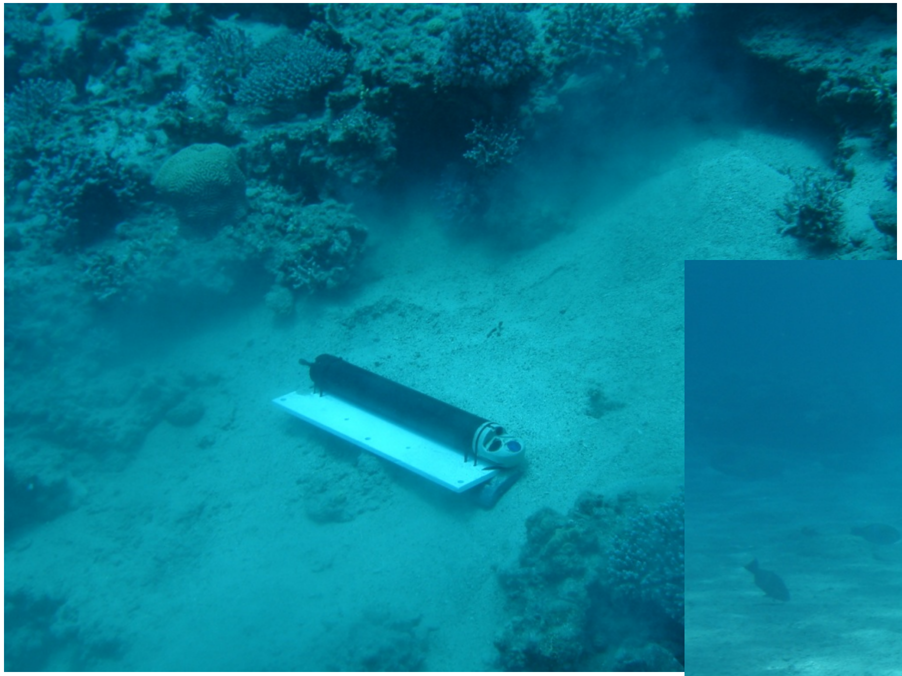
Velocity Range Value

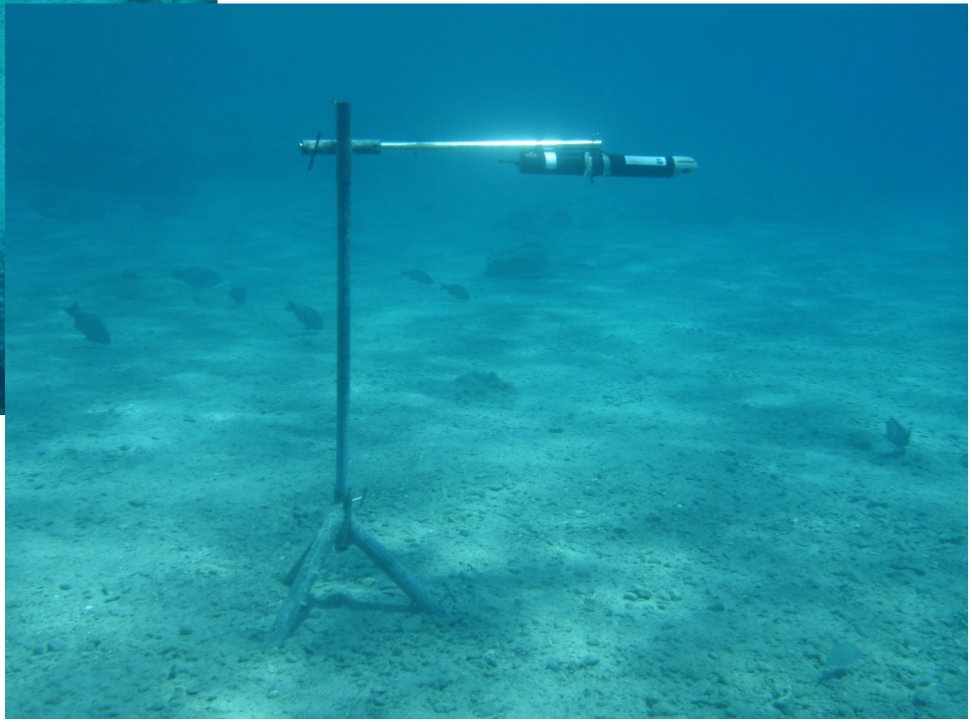
- Prior knowledge of your flow goes a long way in selecting an appropriate range.
- Set the **Velocity Range** slightly higher than expected velocities to avoid ambiguity issues.
- Turbulent flows may require a higher velocity range to achieve reasonable correlations.

Profilers – operating in coherent mode

- Referred to as HR-profilers
- Short range, but can provide time and spatial scales far beyond standard current profilers. Scales are all the way down to 1 cm and time resolution to 8 Hz.
- HR is a firmware upgrade (from Aquadopp profiler)
- The HR is primarily for use by scientists.
- There is much to learn about the HR units but applications in scientific studies are increasing.
    - Bottom boundary layers
    - Direct estimation of turbulent dissipation rates

The HR in its natural environment

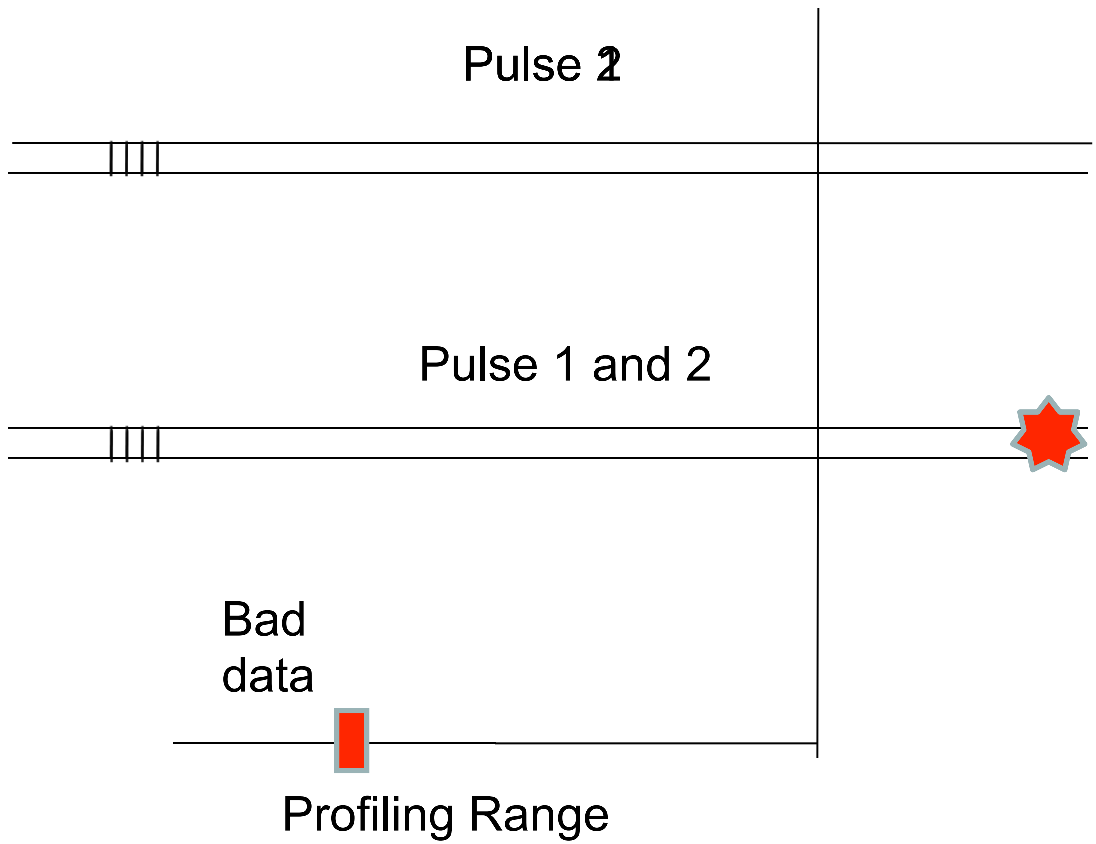




HR-Profilers, implementation

- There are two main issues with the HR systems
  - The product of the velocity range and the profiling range is limited.
  - Pulse-to-pulse interference. The first pulse is not gone when you are listening to the second pulse
- Response in the implementation
  - Try to extend the velocity-range product by introducing ambiguity resolution (“Extended range”)
  - Try to configure the instrument in such a way that pulse-to-pulse interference is avoided.

Pulse-to-pulse interference

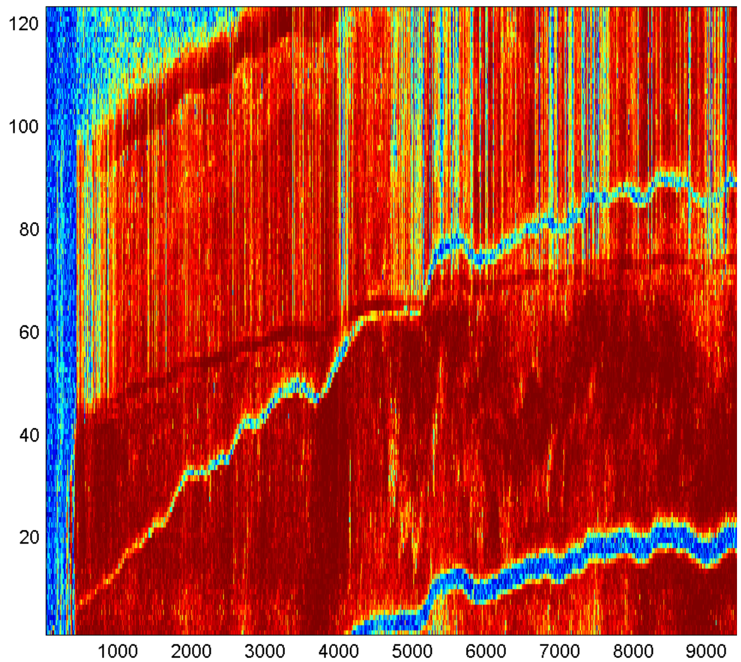


Pulse-to-pulse interference from tidal surface variations

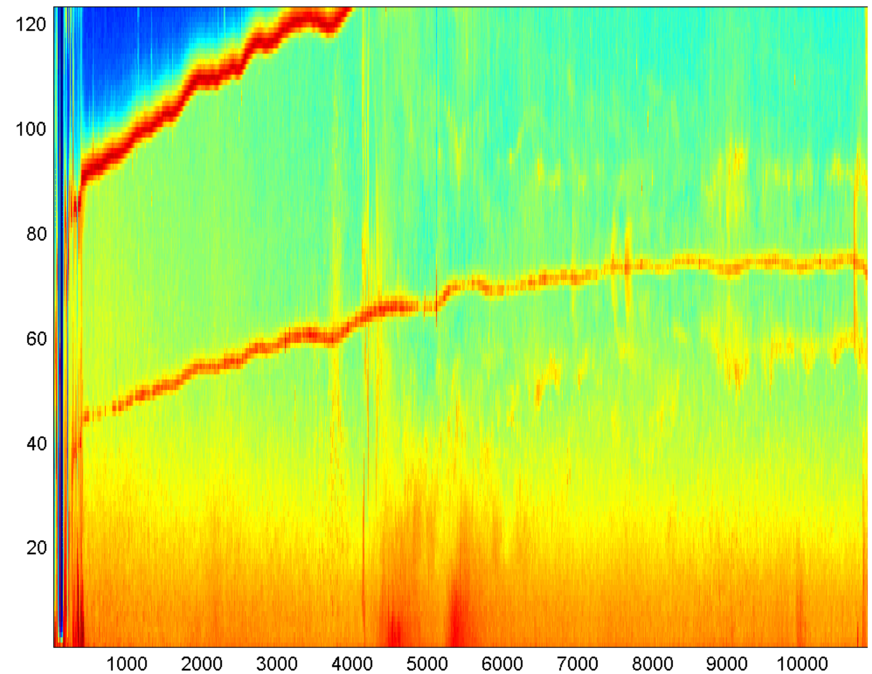
www.nortek.no

True innovation makes a difference

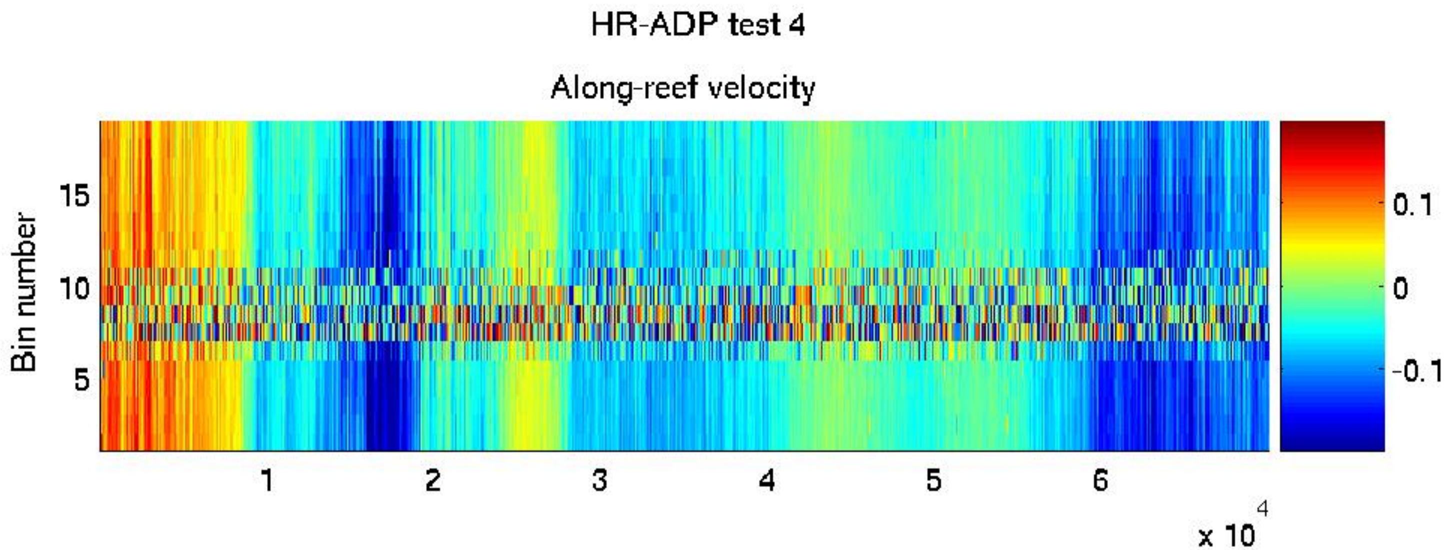
Correlation



Amplitude



Pulse-to-pulse interferences from surface



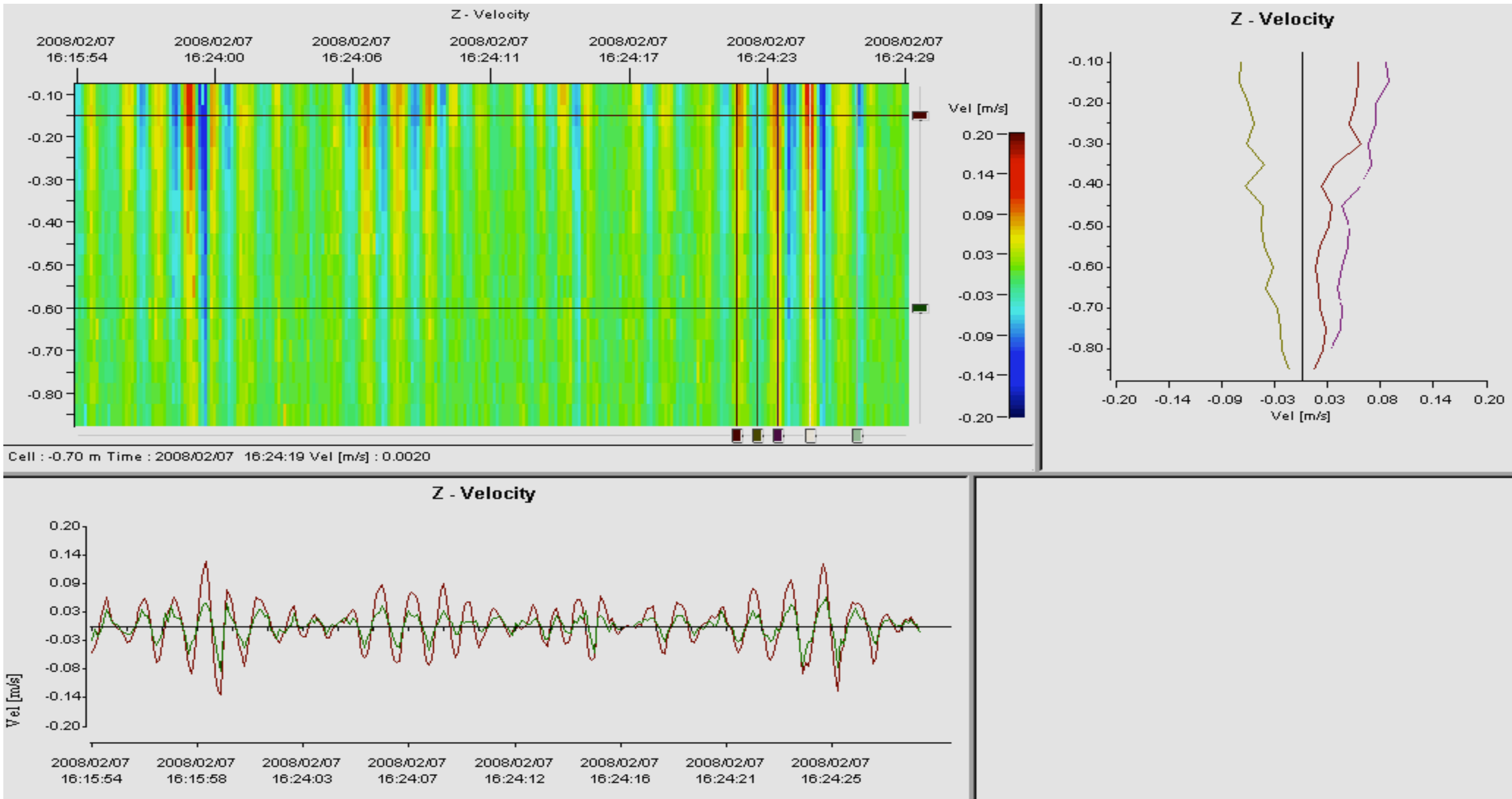
100% data collection goal – less likely to happen with HR profilers

NORTEK AS

www.nortek.no

True innovation makes a difference

Typical pulse coherent data



Coherent systems – main limitation

Phase change $d\phi \in \langle -\pi, \pi]$

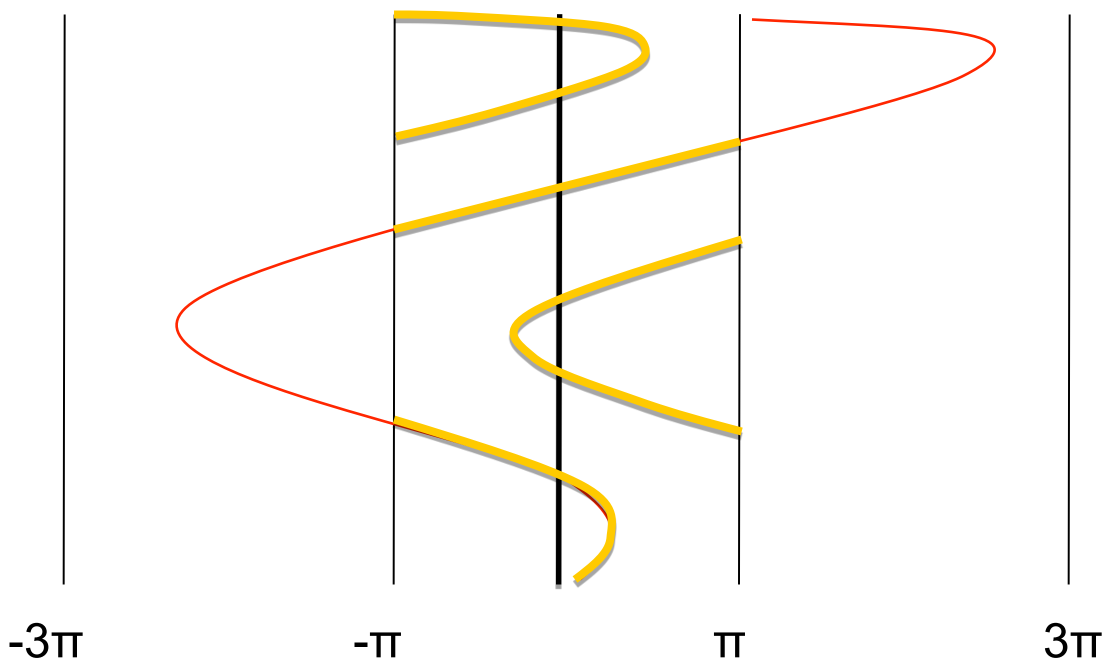
$V = c^* d\phi/\tau$ where τ is time between the two transmit pulses

So V cannot exceed $c^* [-\pi,\pi]/\tau$

Maximum velocity referred to as "ambiguity velocity"

The larger the time separation, the smaller the ambiguity velocity

Ambiguity wrapping



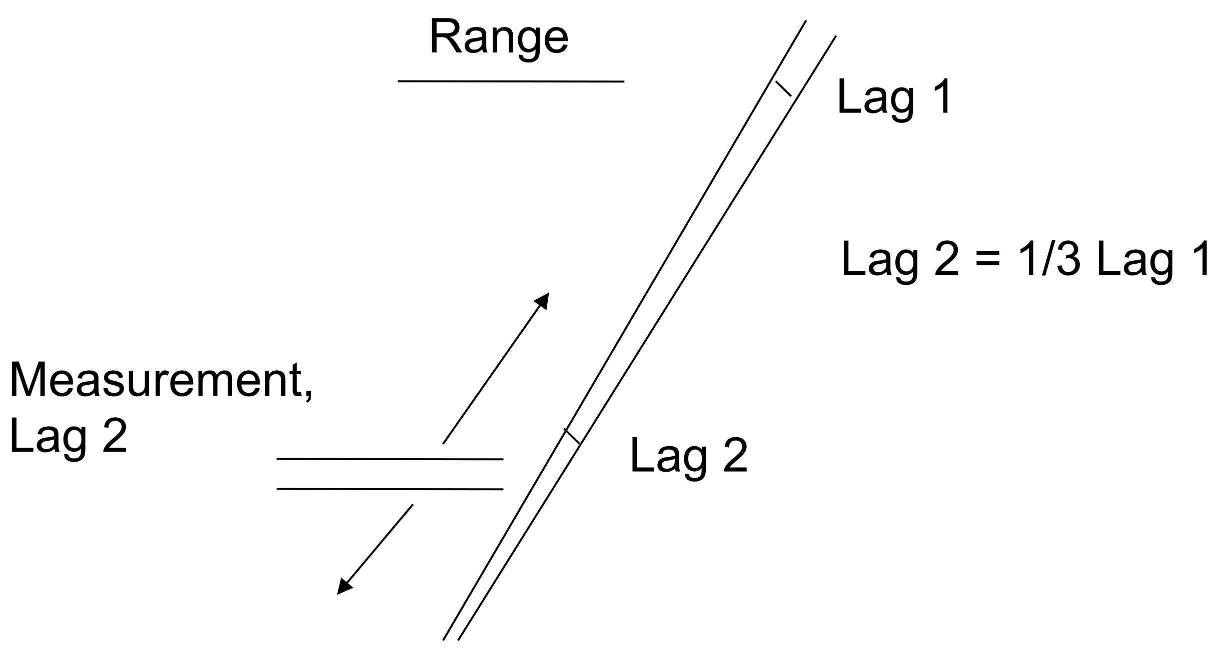
More limitations - decorrelation

- If the lag is too large relative to the intensity of the motion, coherent processing may not work
  - Like taking a picture with slow shutter speed.
- If the pulses ”gets mixed up”, correlation drops
  - Pulse-to-pulse interference
  - The correlation parameter is an important quality parameter for coherent systems

HR profilers - implementation

- Try to extend the velocity range by introducing ambiguity resolution ("extended range")
- Through the use of "Wizard" software, try to ensure that the the instrument is configured in such a way that pulse-to-pulse interference is avoided
- Aim to optimize the performance through optional use of 1,2, or 3 beams
- Implement both on 1 and 2 MHz
- Add large recorder (4GB)

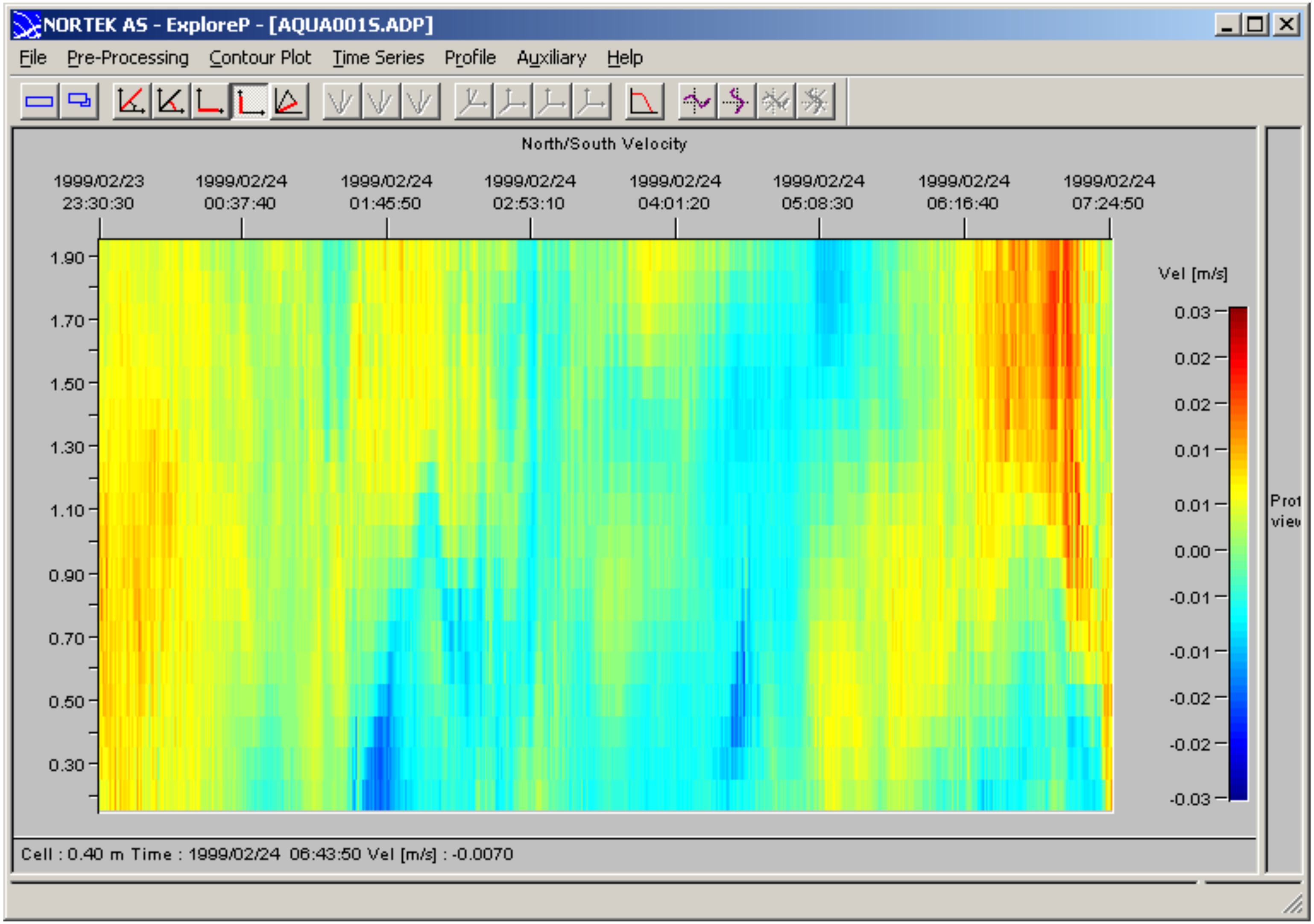
Extended velocity range



Measurement 1 – precise but maybe not the right ambiguity branch

Measurement 2 – less precise but larger velocity range. Extrapolated

Slow flow in harbor



Different systems, different consequences

Velocimeters (= single point sensors):

$\sigma V = \sigma(d\phi(R))/\tau$

- Large pulse separation give very low noise (= precise data)
- But then the velocity range becomes very small

Profilers – range limited to the time between pulses

$Range = \tau * c/2$

- Large lag allow long range but small velocity
- Very short-range profilers

Questions?