High-Speed Velocity Estimation in Optical Doppler Tomography

Embedded Signal Processing Laboratory
Dept. of Electrical and Computer Engineering
The University of Texas at Austin

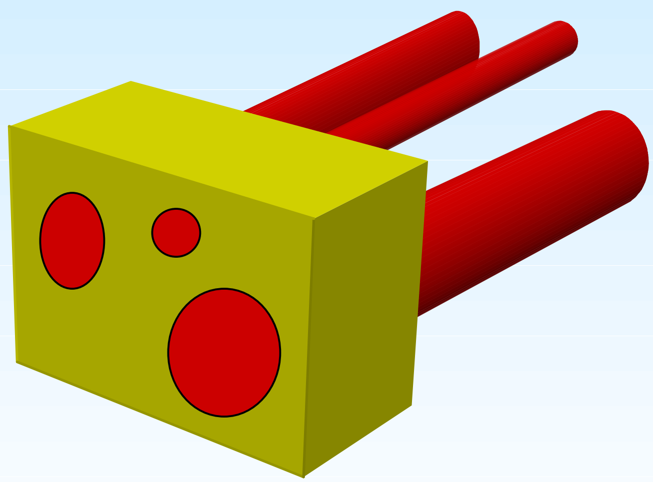
Milos Milosevic, Wade Schwartzkopf, Thomas E. Milner, Brian L. Evans, Alan C. Bovik

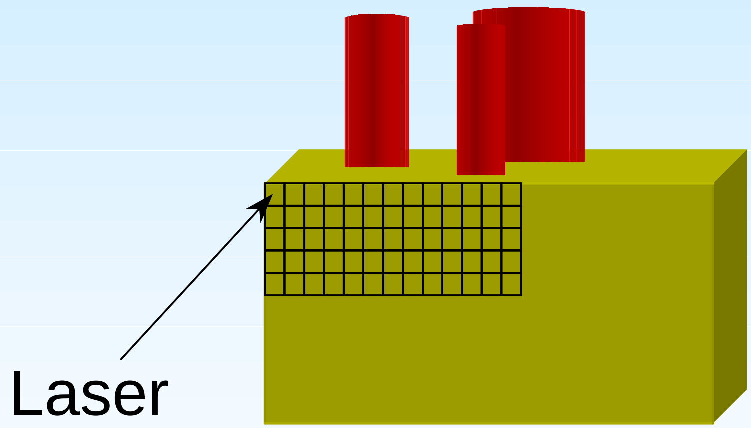
http://signal.ece.utexas.edu/

- Introduction -

Optical Coherence Tomography

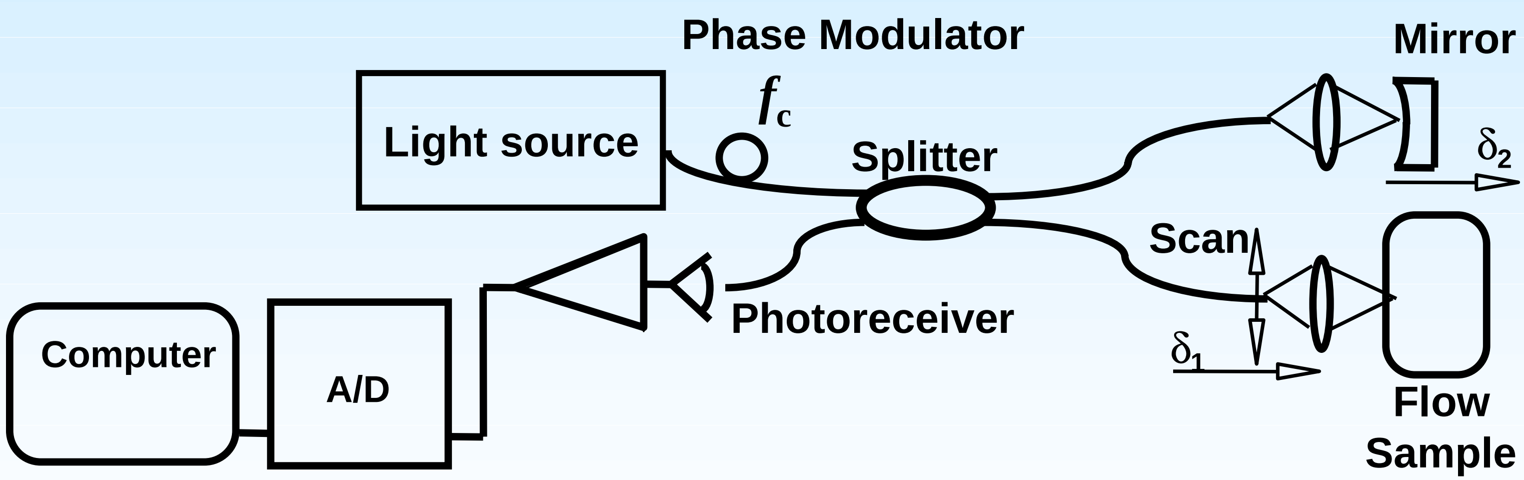
- 3-D imaging of tissue by laser scanning





Optical Coherence Tomography

- Experimental setup - Michelson interferometer
- Splitter correlates reflected and backscattered signals
- Scan depth controlled by mirror position



Need for Speed

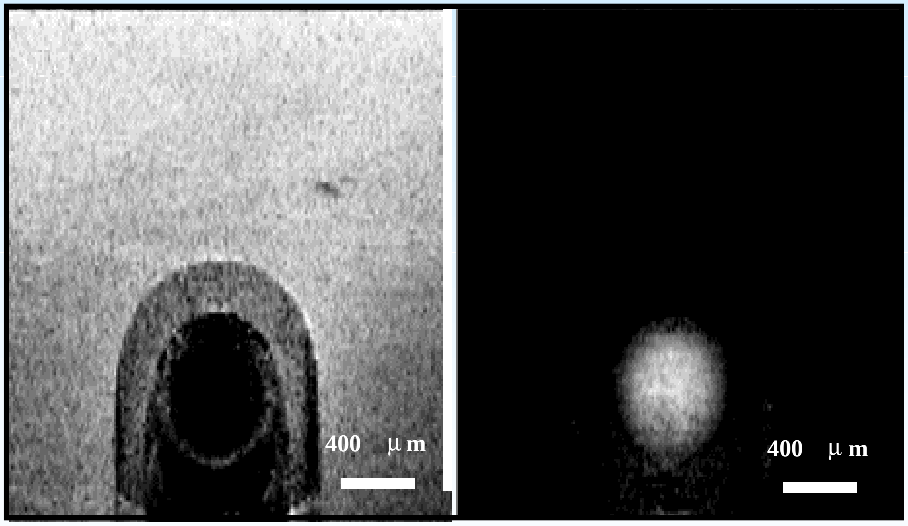
- Higher acquisition speed

Old Systems	New Systems
0.005 frames/s (1 frame every 3 min)	10 frames/s
0.02 s/pixel	10 μs/pixel
f_c = 5 kHz	f_c = 1 MHz
f_s = 20 kHz	f_s = 50 – 100MHz
10 cycles/pixel @ 0.5 kHz min Doppler shift	**0.0013 cycles/pixel** @ 0.5 kHz min Doppler shift
Slow	Fast

- Background -

Structural and Velocity Images

- Structural ⇒ map of tissue density
- Velocity ⇒ map of fluid flow

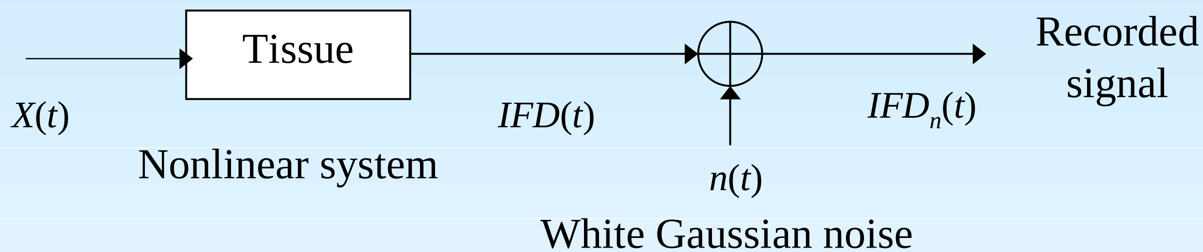


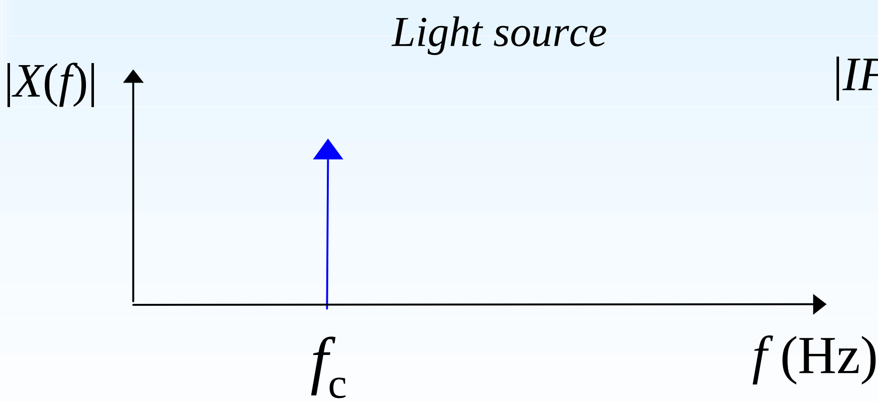
Structural Velocity

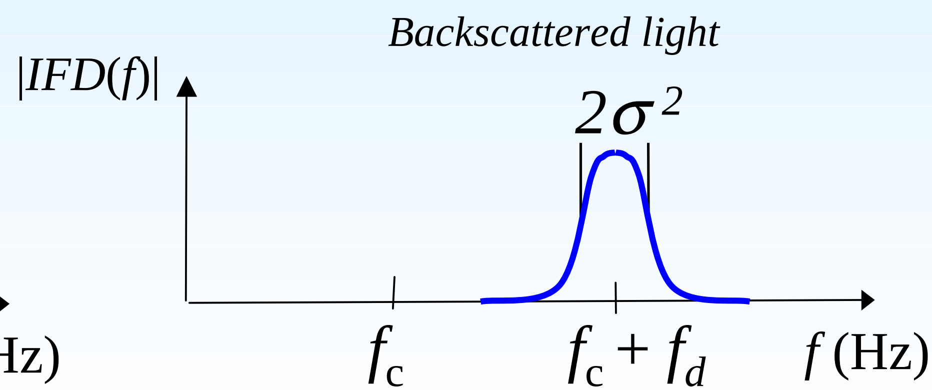
- Background -

Structural and Velocity Images

- Structural image： from amplitude of received signal
- Velocity image： from Doppler shift in received signal







The Faster the Better

- Time of acquisition/pixel = $t_a \propto 1/(f_c+f_d)$ seconds
  - f_d is a function of fluid motion
  - f_c is a free variable under operator control
- Increasing f_c *decreases* time of acquisition/pixel
- Large $f_c \rightarrow f_d \ll f_c$
- Hard to detect f_d : ~ 0.0013 cycles of f_d in t_a
- Linear methods (e.g. based of the FFT) do not have enough frequency resolution

Proposed Algorithm

1. For every pixel in the ODT velocity image,
   a. Record $IFD_n(t)$ for a pixel.
   b. Record $IFD_n(t+\Delta t)$ for the same pixel.
   c. Find cross-correlation of $IFD_n(t)$ and $IFD_n(t+\Delta t)$, $R_T(\tau+\Delta t)$.
   d. Find location of the first peak of $R_T(\tau+\Delta t)$.
   e. Estimate Doppler shift $\Rightarrow$ grayscale pixel value
2. Perform 3×3 median filtering on the ODT velocity image.
3. 2-D phase unwrapping to refine Doppler shift estimate.

Estimating Doppler Shift

- Estimate Doppler shift for a single pixel

$$\hat{f}_d = \mathrm{mod}\left(f_d \Delta t, 1\right) = \frac{\mathrm{mod}\left(f_c \Delta t, 1\right) - f_c \tau_{\max}}{\tau_{\max} - \Delta t}$$

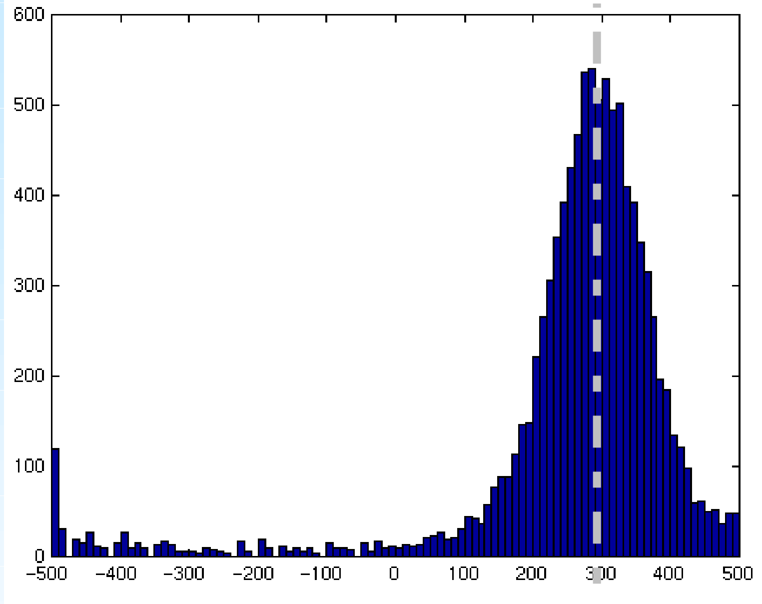
where

$$\tau_{\max} = \underset{\tau}{\arg\max}\, R_T\left(\tau, \Delta t\right)$$

Proposed Algorithm - Reliability

- Doppler shift f_d = 300 Hz
- Carrier f_c = 1 MHz
- SNR = -3 dB
- Simulation = 10,000 trials

Histogram of Estimates



f (Hz)

f_d=300Hz

Algorithm Limitations

- The range of detectable phase shifts/pixel

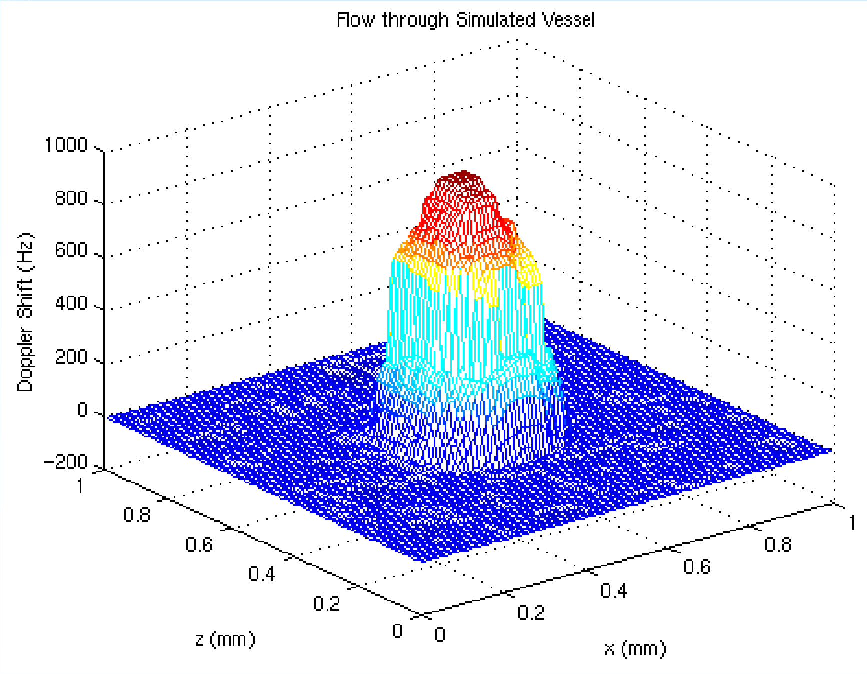
$$-0.5 < f_d \Delta t \leq 0.5$$

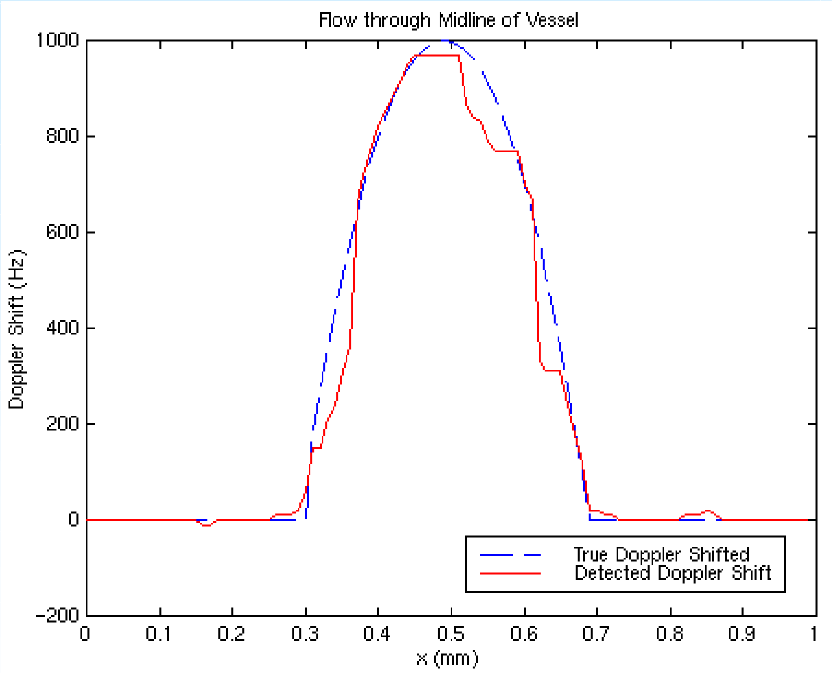
- Limited range causes phase wrap-around
- The algorithm employs phase unwrapping
- The algorithm frequency resolution is

$$\Delta f_d = \frac{f_c}{f_s \Delta t}$$

Simulated Results

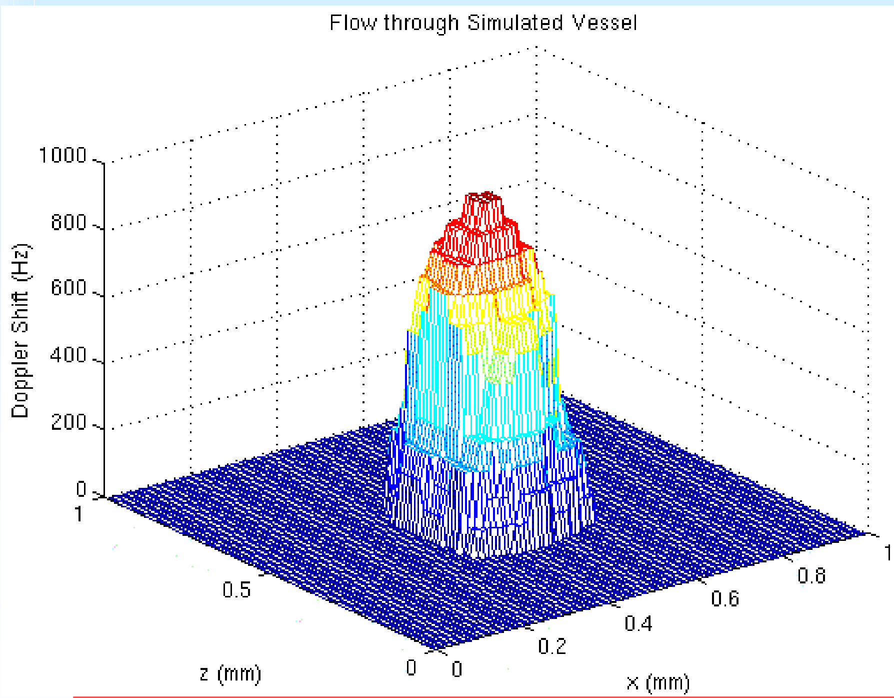
- Computation: 32 bits/sample, double precision floating point; Sampling: 128 samples @ f_s = 100 MHz; Noise: SNR = -3 dB

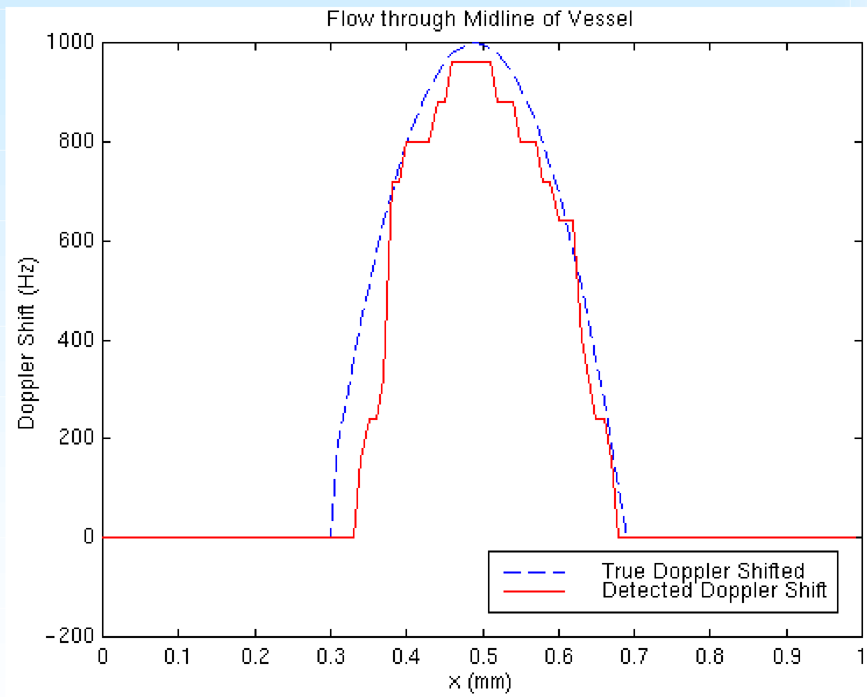




Simulated Results

- Computation: 4 bits/sample, 16 bit arithmetic; Sampling: 16 samples @ f_s = 12.5 MHz; Noise: SNR = -3 dB





Conclusions

- Velocity estimation robust to
  - SNR
  - Bit precision in data acquisition
  - Data record length
- Computationally efficient algorithm
  - Real-time implementation on a high-end digital signal processor or PC
  - Fixed-point computation using 16-bit arithmetic