

Extracting lateral motion from the dynamic amplitude modulations – the dynamic speckle – of a PDV signal

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ABSTRACT

Photon Doppler velocimetry (PDV) is a robust measurement technique that is used for the sensing axial motion in a variety of test applications. This presentation reviews the mechanics of standard PDV and then introduces the concept of lateral velocimetry, as it relates to laser speckle dynamics, since it may potentially be incorporated into existing PDV sensing systems. In other words, it may be possible that lateral velocimetry capabilities are added to existing PDV sensor architectures without requiring any drastic changes in hardware or architecture. The topic is introduced conceptually, experiments are performed, and an analysis of experimental results acts as a proof of concept.

OUTLINE

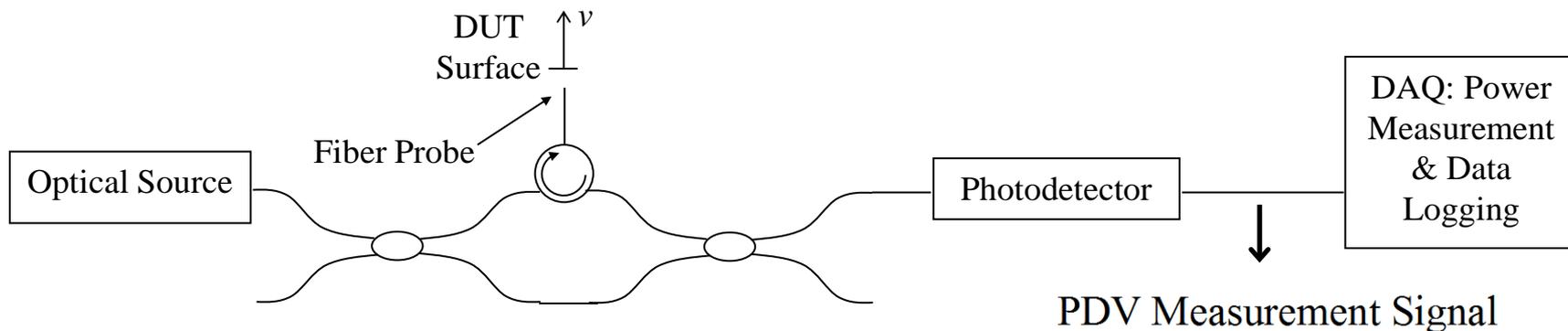
- Motivation
- Background
- Sensing Methodology
- Experiment
- Results
- Conclusions

MOTIVATION

- Robustness, capability, and versatility of PDV make it particularly well-suited for certain sensing applications
- Velocity measurement is generally limited to laser beam's propagation axis
- Lateral velocity data would be good to have, particularly if this capability could be attained without any change to the current PDV hardware
 - If successful, it is possible that old PDV data could be 'mined' for lateral velocity information
 - Even qualitative information, such as an indication of whether or not any lateral motion is present, could prove useful
 - Currently, lateral-directionality constitutes a long-term goal

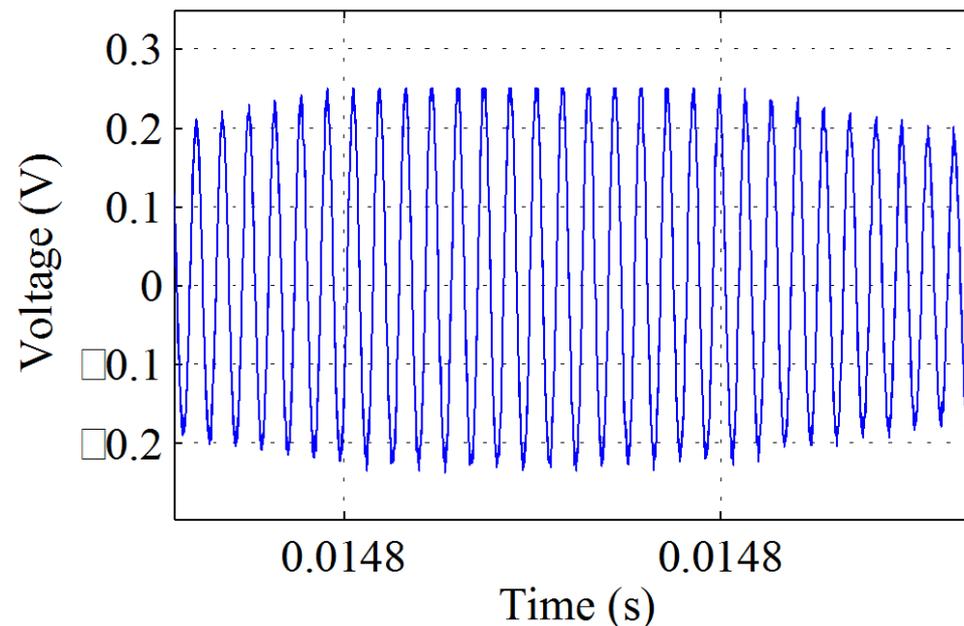
BACKGROUND I

Referenced PDV sensor architecture:



DUT motion generates interference fringes, the spacing of which are proportional to the axial velocity

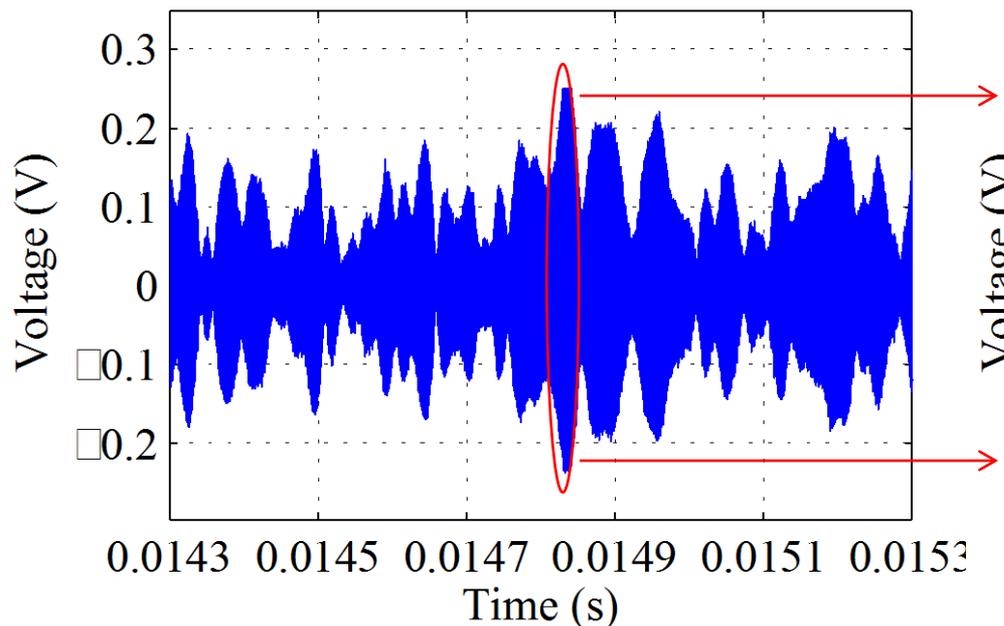
To date, PDV systems are not utilized for the measurement of lateral velocities



BACKGROUND II

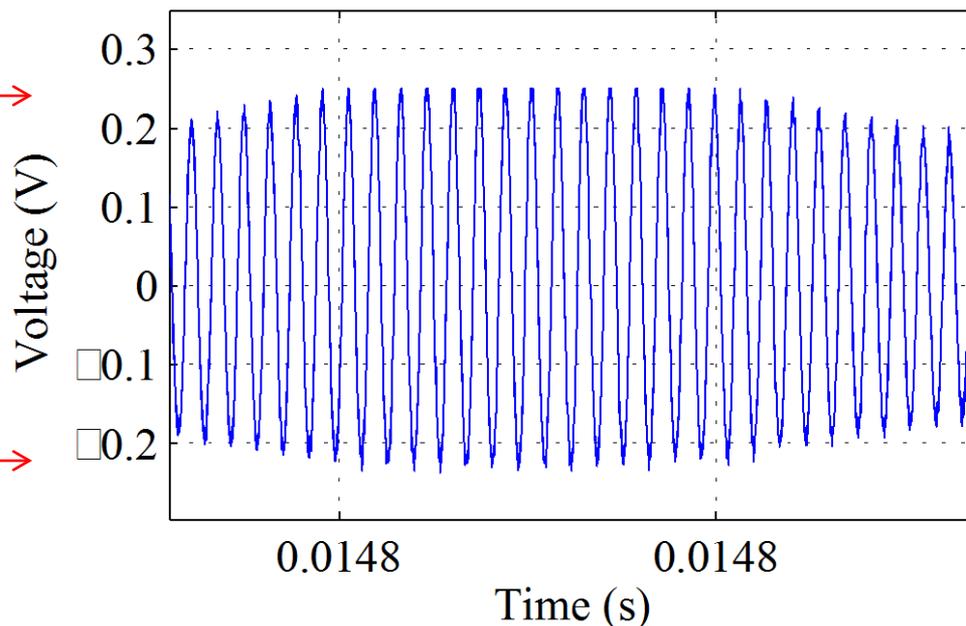
There is a dynamic, speckle-based structure in standard PDV measurement signals that is independent of the DUT's longitudinal velocity

PDV Measurement Signal



↑ *Caused by ??*

PDV Measurement Signal



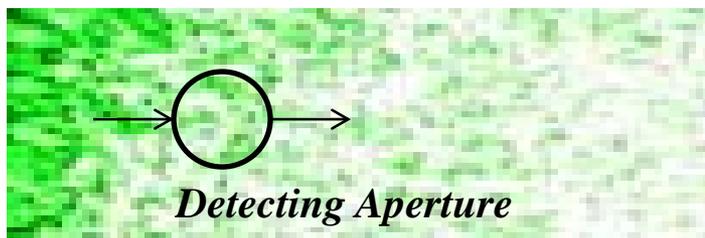
↑ *Caused by axial motion*

Low-frequency structure super-imposed on high-frequency PDV signal

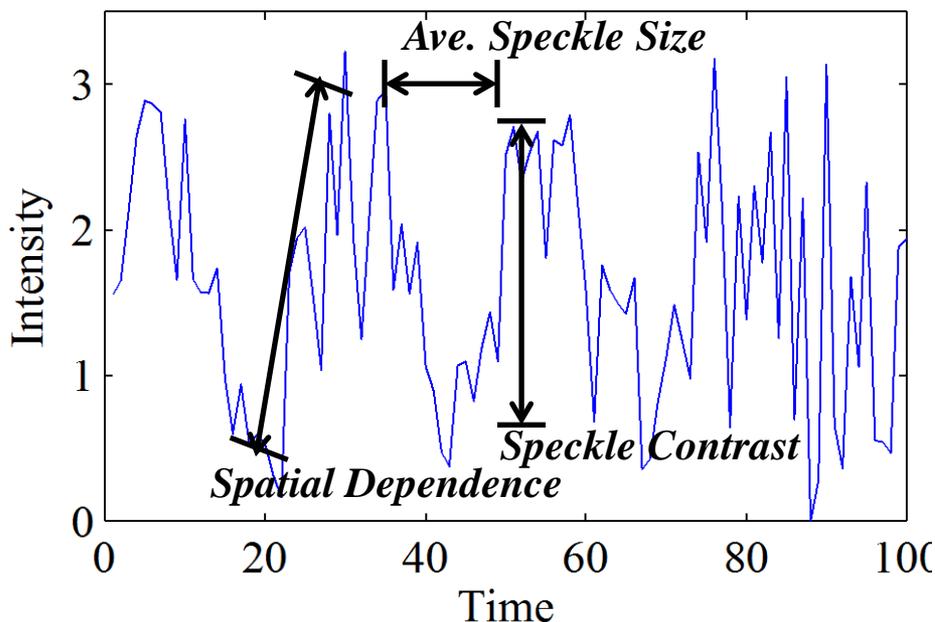
BACKGROUND III

- Speckle dynamics have been related quantitatively to target dynamics under special circumstances (*Fercher, 1980; Iwai et al., 1980; Iwai et al., 1981*)
- One researcher in particular, noted the potential for exploiting distinct elements of a single measurement signal to simultaneously and independently measure lateral and axial velocity components (*Briers, 1995; Briers, 2007*)
- With advances in technology, we hope to bridge the gap between initial research in the 1980's and 1990's, follow-up research, and deployment
 - We will extend previous analyses to include the use of heterodyning, as in PDV
 - We will improve on initial research, which was limited to highly-controlled laboratory environments and velocities on the order of 1 m/s
 - Robustness and a full-performance space were never characterized
- The bottom line is that we want to establish whether this method will quantify any lateral velocity (if present) and indicate zero lateral velocity otherwise

SUMMARY OF SENSING METHODOLOGY



Random Fluctuations in Measured Intensity

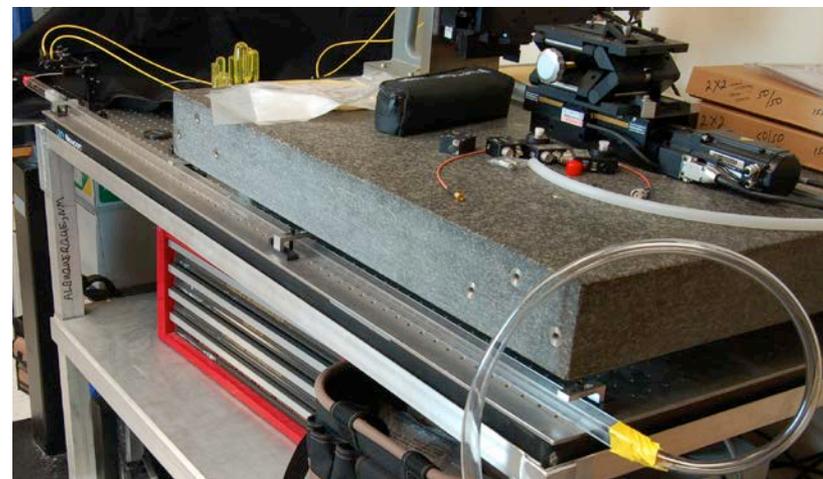
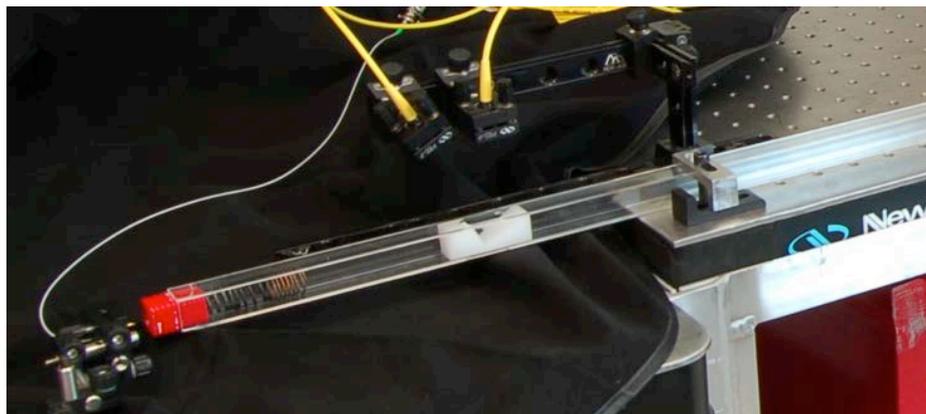
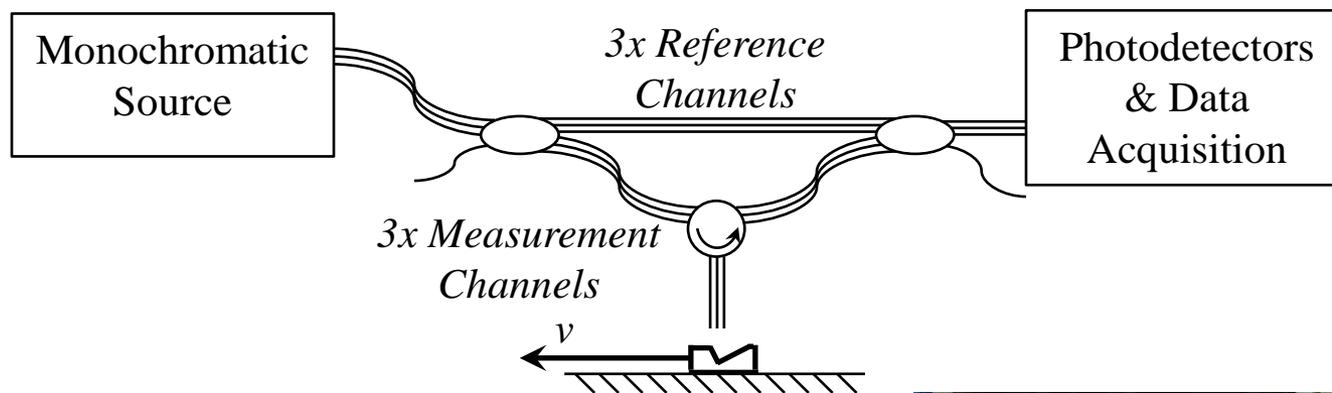


Lateral motion results in boiling and translation, and yields:

1. Variation in the measured intensity, whose statistics (e.g., variance, correlation time, etc.) are related to several parameters, including velocity (*Fercher, 1980; Iwai et al., 1980, 1981*)
2. A series of light and dark spots, the frequency of which is largely based on (1) the velocity and (2) the average speckle size
3. Speckle blurring, reducing the measured contrast (*Briers, 1996, 2007*)

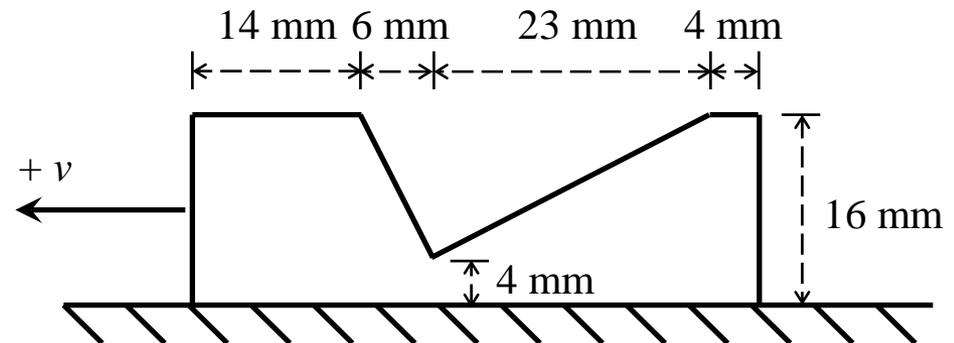
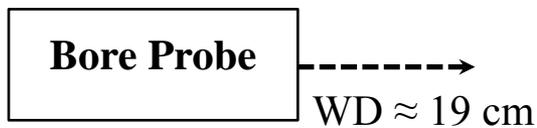
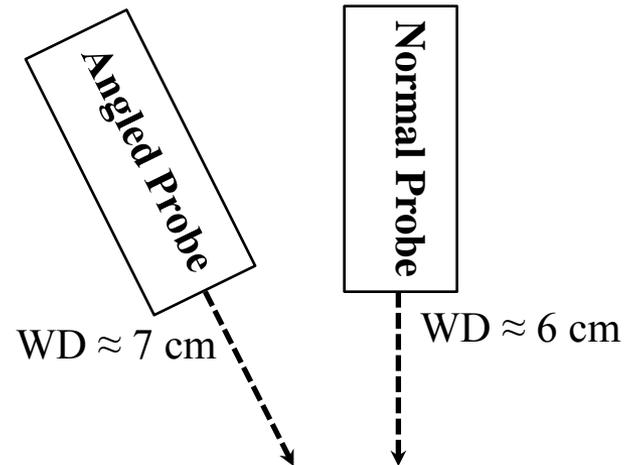
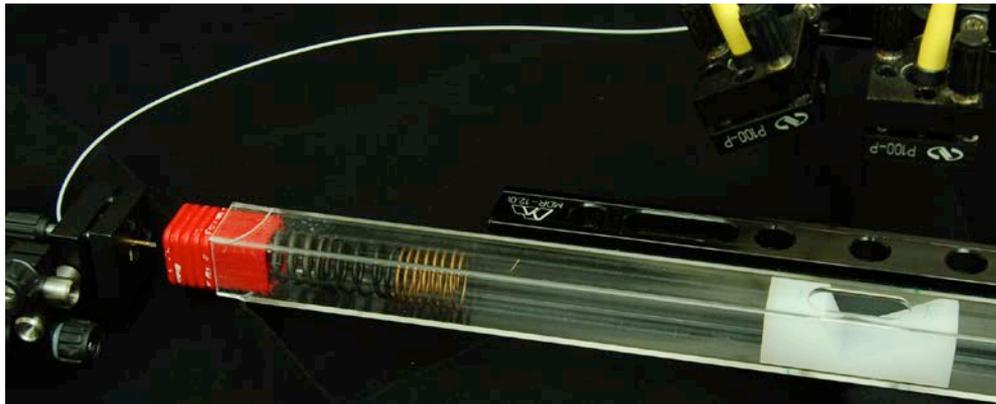
EXPERIMENT I

- Collimating probes; spot size $< 500 \mu\text{m}$; working distance between 5-20 mm
- CW laser output power = 1.33 W per channel at 1550 nm
- Sampled at 200 MHz; for 5-20 ms depending on projectile velocity (2-20 m/s)



EXPERIMENT II

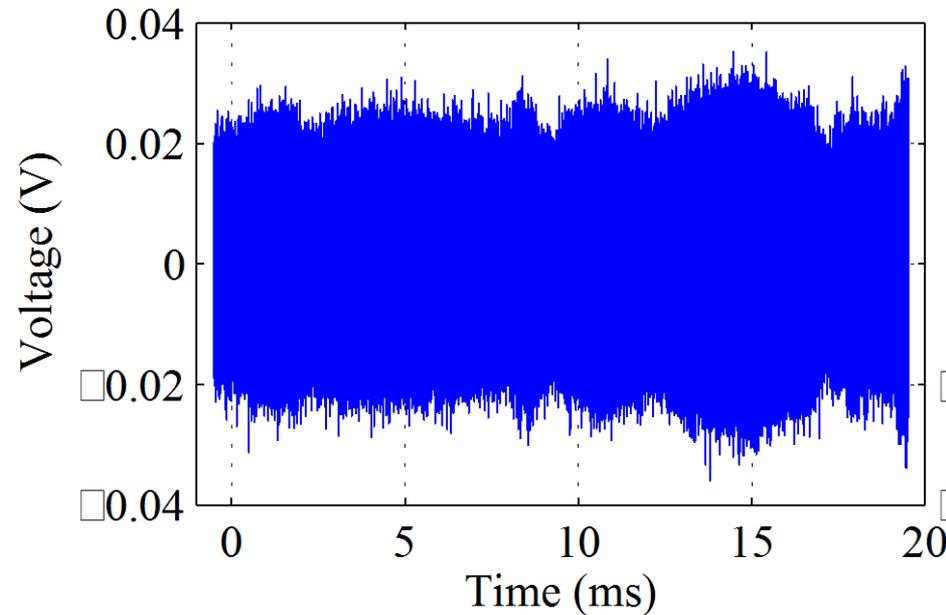
The arrangement of probes and the geometry of the projectile offer insight into the capabilities of the proposed sensing methodology



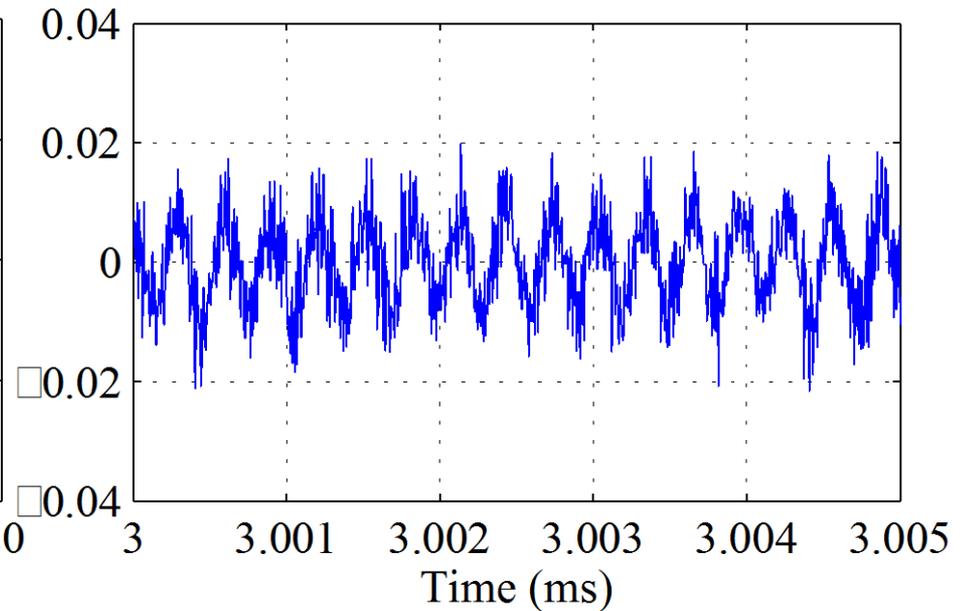
RESULTS – BORE PROBE I

- Standard PDV Channel: This serves as a reference channel in a sense
 - Well-established theoretical understanding
- SNR increases marginally as projectile nears fiber probe

Bore Probe: Slow Velocity



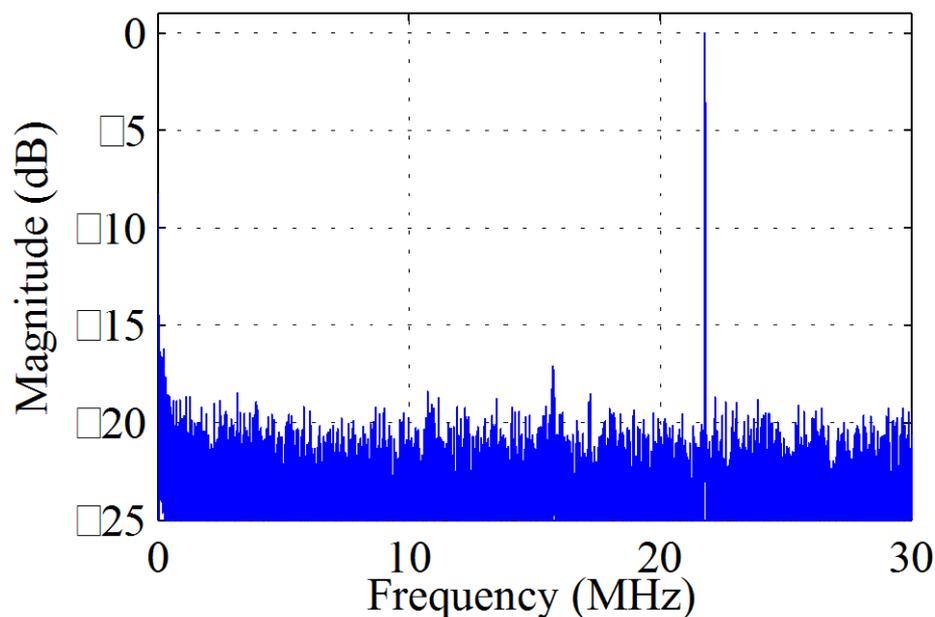
Bore Probe: Slow Velocity, Detail View



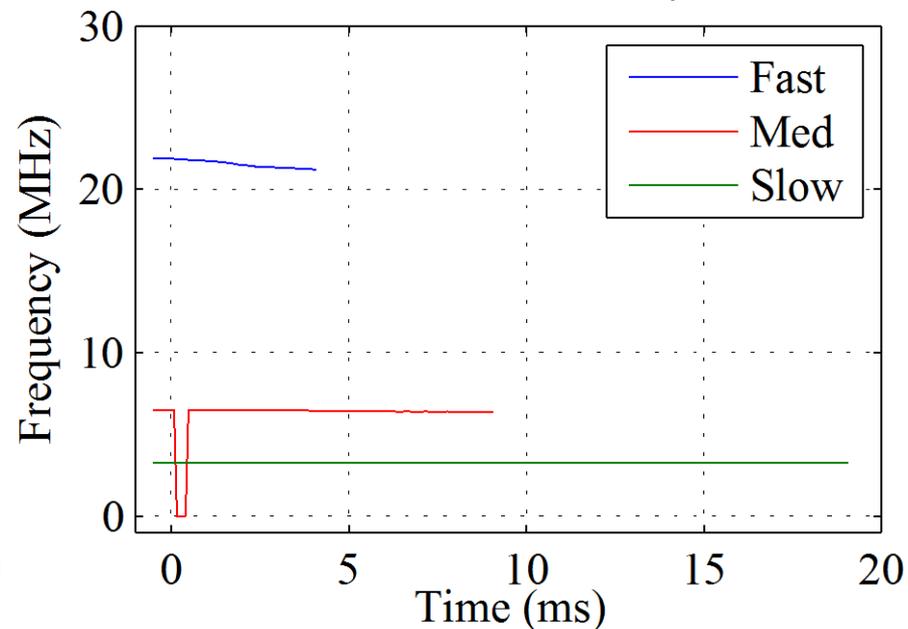
RESULTS – BORE PROBE II

- No ambiguity in FFT
 - Peak-tracking algorithm records the velocity as a function of time
- No immediately-obvious “speckle-dependence”

Bore Probe: Normalized FFT, Fast

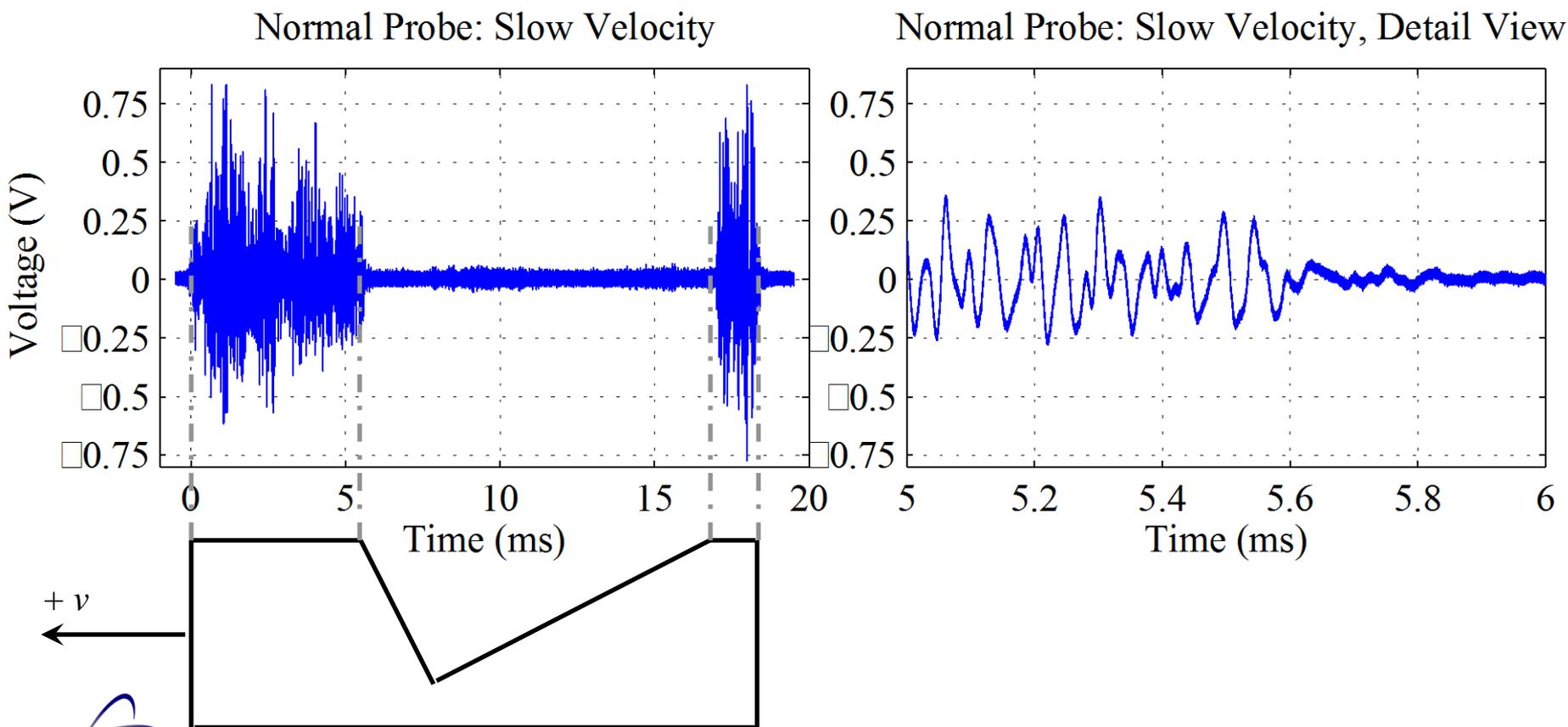


Bore Probe: Location of Primary Peak in FFT



RESULTS – NORMAL PROBE I

- Note, the loss of SNR during inclined measurement
- Note, also, the edge-regions where the beam spot likely encounters an edge

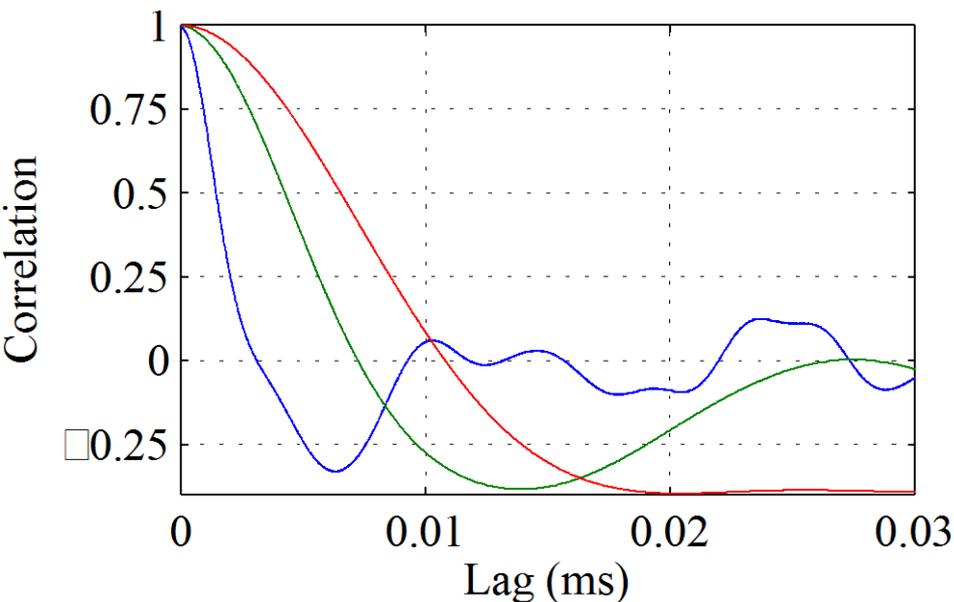


RESULTS – NORMAL PROBE II

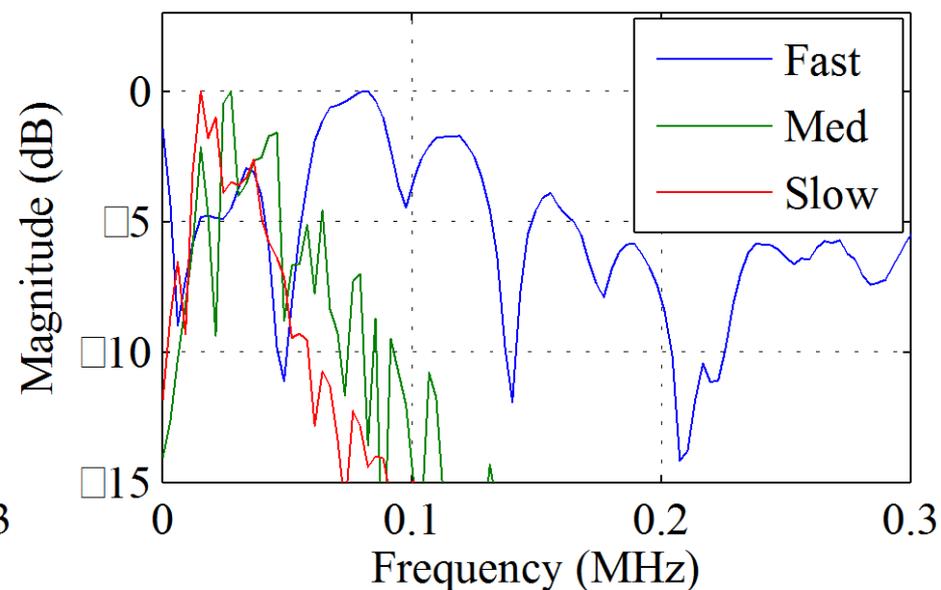
An increase in velocity results in:

- (1) Decrease in correlation time, and
- (2) Increase in the center frequency of the low-frequency content

Normal Probe: Normalized Autocorrelation



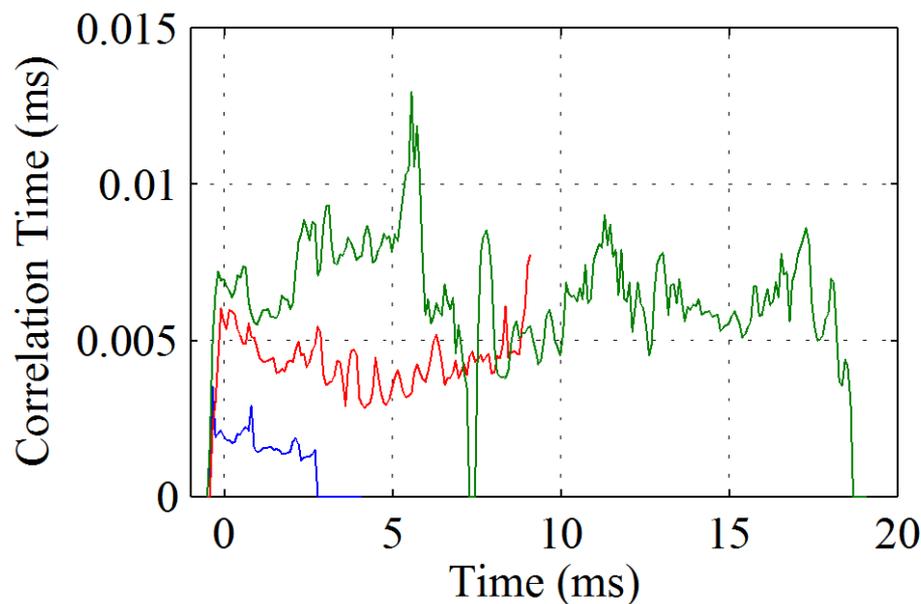
Normal Probe: Normalized FFT



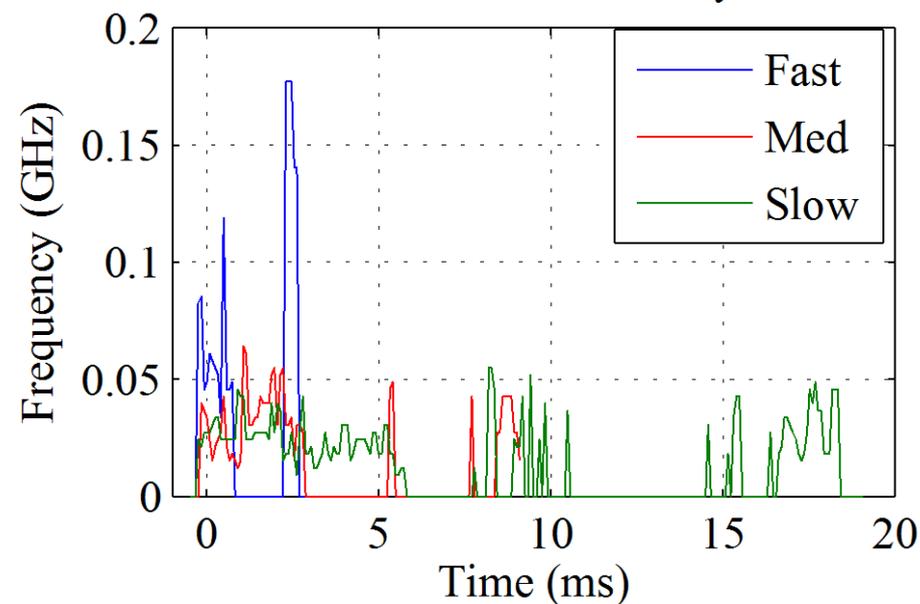
RESULTS – NORMAL PROBE III

- Measurement qualitatively separates fast-, medium-, and slow-velocity trials
- Autocorrelation outperforms FFT
 - (1) Less noise and (2) more robustness during low-SNR regions

Normal Probe: 40% Correlation Time



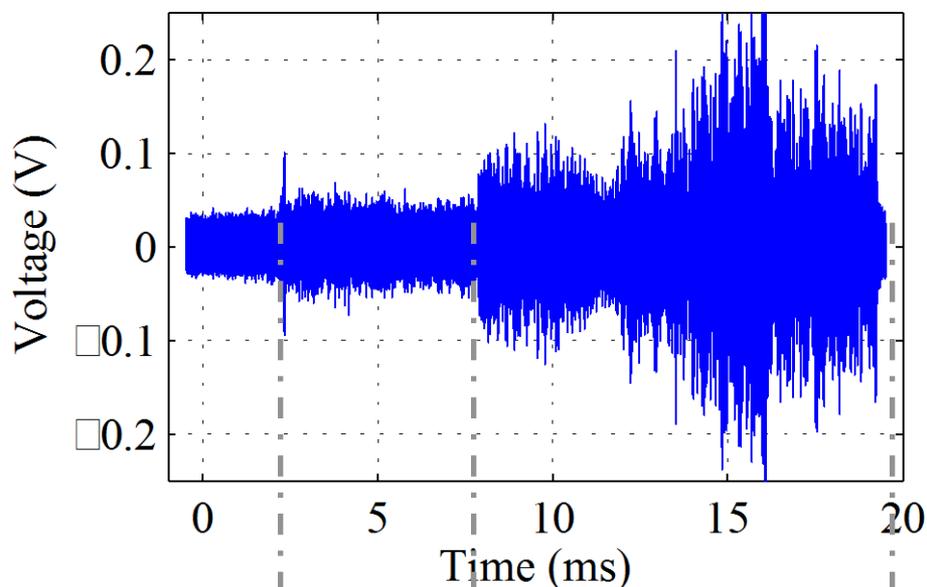
Normal Probe: Location of Primary Peak in FFT



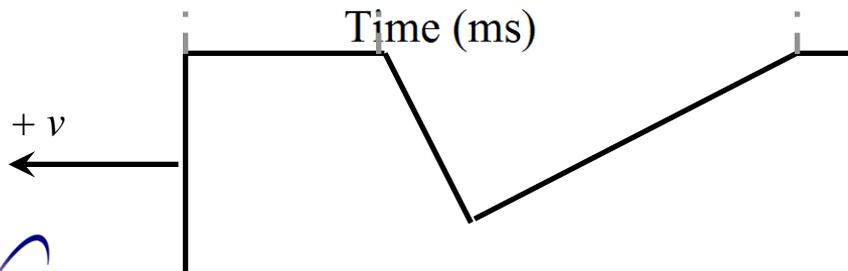
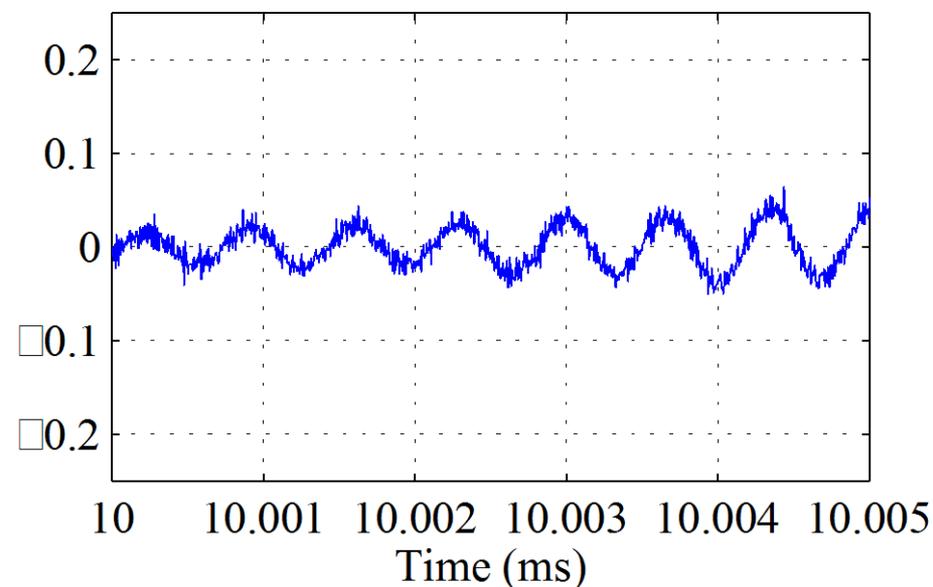
RESULTS – ANGLED PROBE I

- Signal includes multiple components, operating at different time-scales

Angled Probe: Slow Velocity



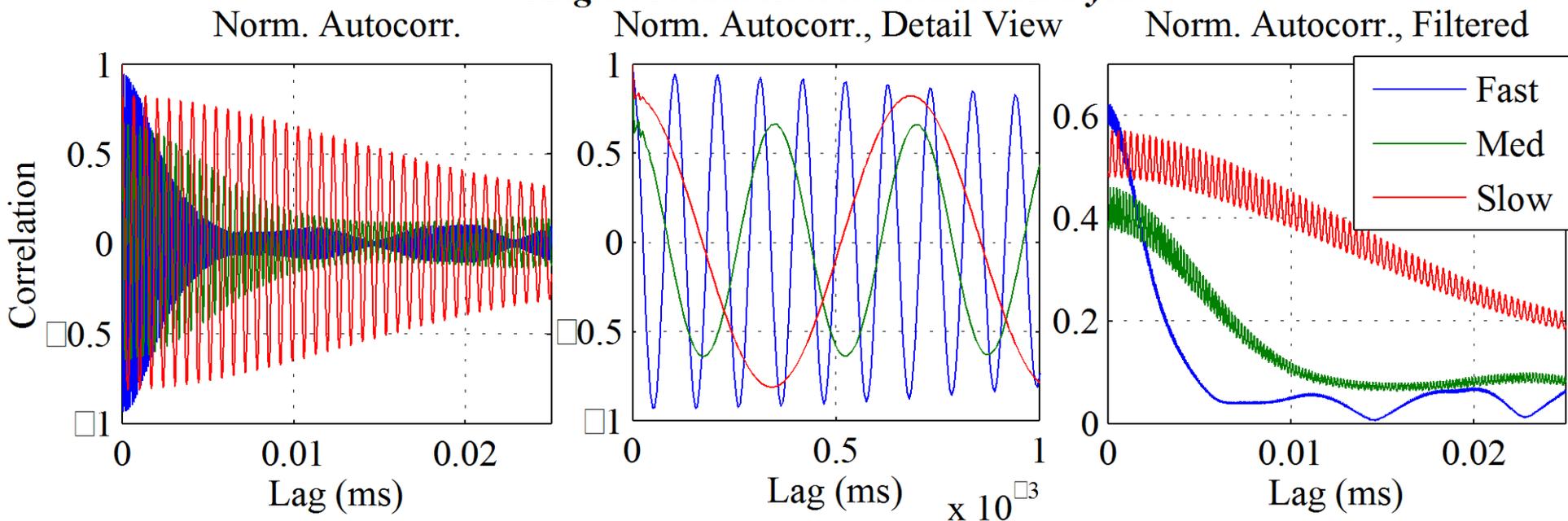
Angled Probe: Slow Velocity, Detail View



RESULTS – ANGLED PROBE II

- Autocorrelation shows low-frequency speckle-based modulation as an envelope over the high-frequency Doppler-based modulation
- Filtering, as an example, can mine out low-frequency speckle-based content

Angled Probe: Autocorrelation Analyses



RESULTS – COMPARISON BETWEEN PROBES

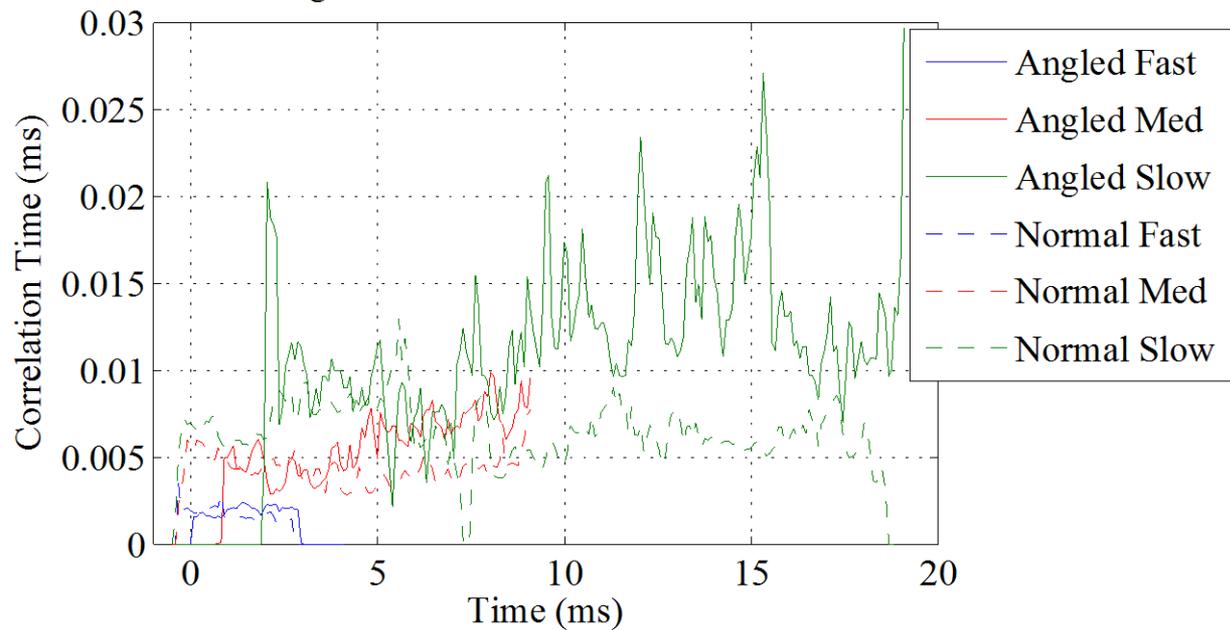
• Axial Velocity

• Demonstrates PDV capability and scales with Bore Probe by $1/(2.2)=0.45=\sin(27)$

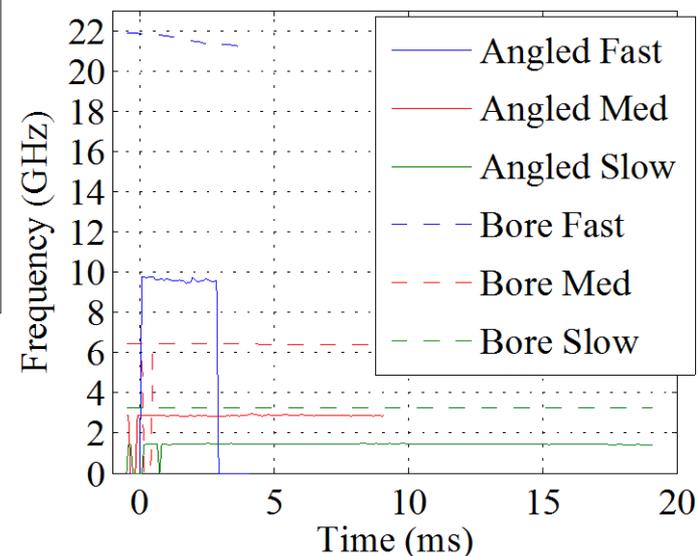
• Lateral Velocity

• Demonstrates (at least qualitative) speckle-velocimetry with filtered autocorrelation

Angled Probe: 40% Correlation Time



Angled Probe: Location of Primary Peak in FFT



CONCLUSIONS

- We demonstrated that the lateral velocity is embedded in multiple speckle-based features, including frequency content and correlation time
 - Performance is validated by the bore probe's standard PDV setup
 - Velocities of ~ 20 m/s were measured with no apparent upper-limit
- The angled probe demonstrates the ability to separate high-frequency (PDV) content and low-frequency (speckle) content, thereby simultaneously measuring axial and lateral motion, respectively

Future Work:

- Use signal processing to better demonstrate separation of lateral and longitudinal velocity components
 - How do I know which velocity component is present and to what extent?
- Quantify performance limits
- Test robustness and, in particular, any dependence on surface properties

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