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Title: New Developments in Photon Doppler Velocimetry (PDV)

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New Developments in Photon Doppler Velocimetry (PDV)

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Abstract

Photon Doppler velocimetry (PDV) has made the transition among many experimental groups from being a new diagnostic to being routinely fielded as a means of obtaining velocity data in high-speed test applications. Indeed, research groups both within and outside of the shock physics community have taken note of PDV's robust, high-performance measurement capabilities. As PDV serves as the primary diagnostic in an increasing number of experiments, it will continue to find new applications and enable the measurement of previously un-measurable phenomena. This paper provides a survey of recent developments in PDV system design and feature extraction as well as a discussion of new applications for PDV. More specifically, changes at the system level have enabled the collection of data sets that are far richer than those previously attainable in terms of spatial and temporal coverage as well as improvements over PDV's previously measurable velocity ranges. And until recently, PDV data have been analyzed almost exclusively in the frequency-domain; although the use of additional data analysis techniques is beginning to show promise, particularly as it pertains to extracting information from a PDV signal about surface motion that is not along the beam's axis. (LA-UR 13-21198)

Acknowledgments

- **Conference Chairs**: Rip Collins, David Moore, and Choong-Sik Yoo
- **Postdoc Mentors**: Matt Briggs and Larry Hull
- **Contributing PDV Experts**: Ed Daykin, Dan Dolan, David Holtkamp, Patrick Mercier, Mike Shinas, Ted Strand, Geoff Taber, and Tony Whitworth

Outline

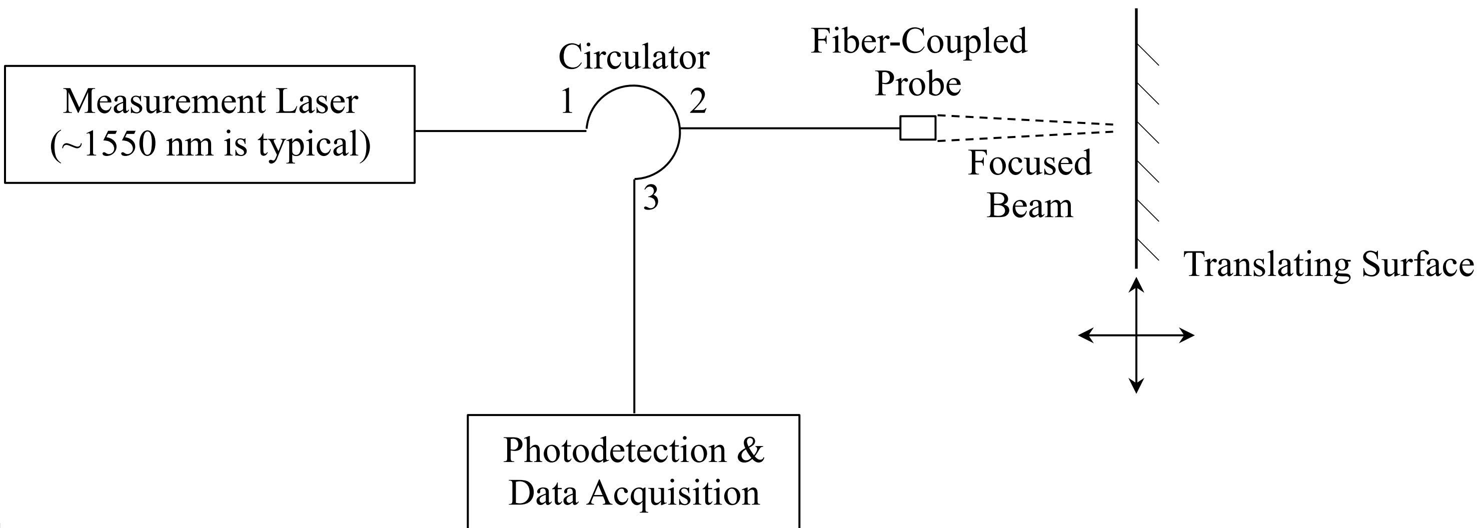
- Background
- Developments
  - System Level
  - Data Analysis
  - Speckle Dynamics
  - New Applications
- Ongoing Challenges for PDV
- Conclusion

Background:
History

- PDV architecture was first used for fluid flow measurements in 1964-65
    - Ted Strand introduced the modern version in Rev. Sci. Instrum. *(Strand, 2006)*
    - LANL systems have been developed/refined, following Strand's innovation, since 2004
- There has been a tremendous increase in PDV usage since its introduction
    - Motivating factors include: relatively low system costs, ease of implementation, robustness in adverse experimental conditions, and a single send and receive fiber
- As several researchers have recently pointed out to me, PDV is no longer considered a "new diagnostic", but rather, its implementation is becoming routine
    - Indeed, my colleagues field PDV on a variety of tests on a weekly (or daily) basis
    - Just a few years ago, 10-20 channels of PDV returning good quality data was considered a big effort, and by way of contrast, today you would need >150 channels measuring a single dynamic event to break into new territory

Background:
Operating Principles

- PDV is used in high-velocity (shockwave) and low-velocity (mechanical vibration) test scenarios
- PDV employs an interferometer to create Doppler-induced beats
  - We relate beat frequencies to the surface's displacement along a probe's beam axis
  - Frequency upshift PDV, or heterodyne PDV, was first introduced by E. Daykin and C. Perez (Daykin, 2008) and implemented early on by P. Mercier et al. (Mercier, 2008)
    - Removes directional ambiguity and while offering superior temporal resolution



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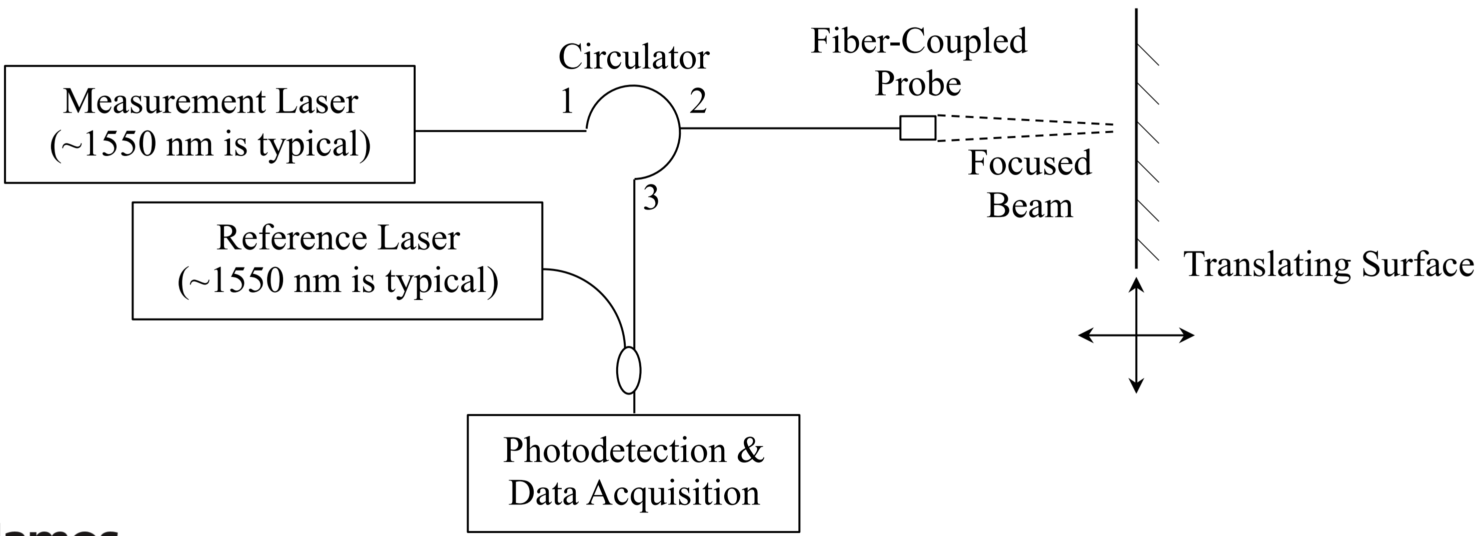
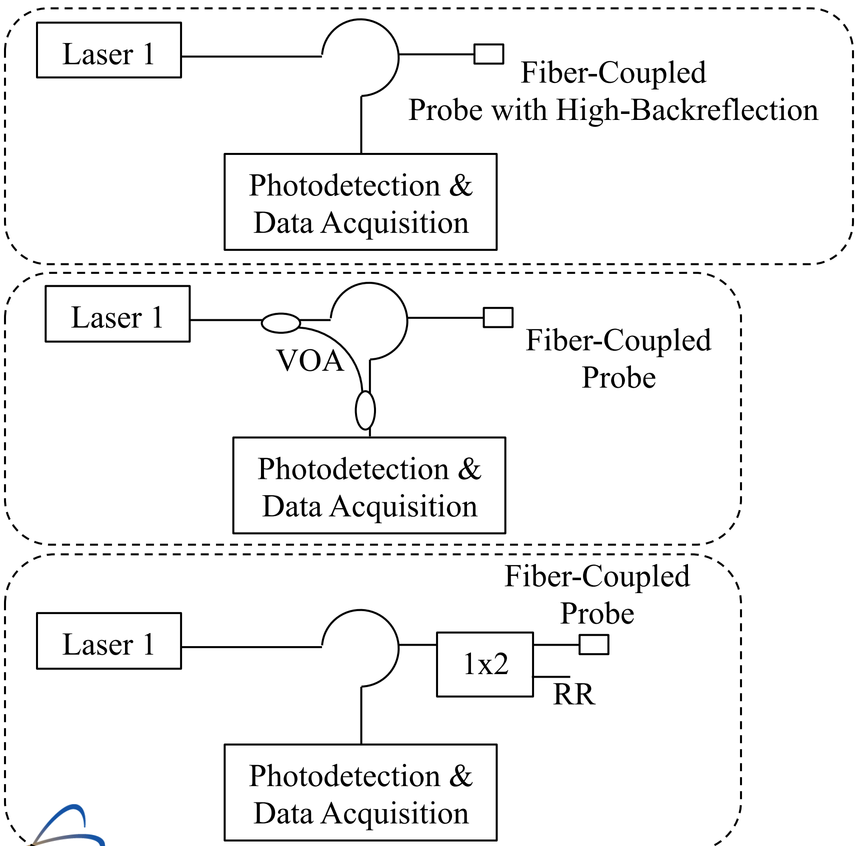


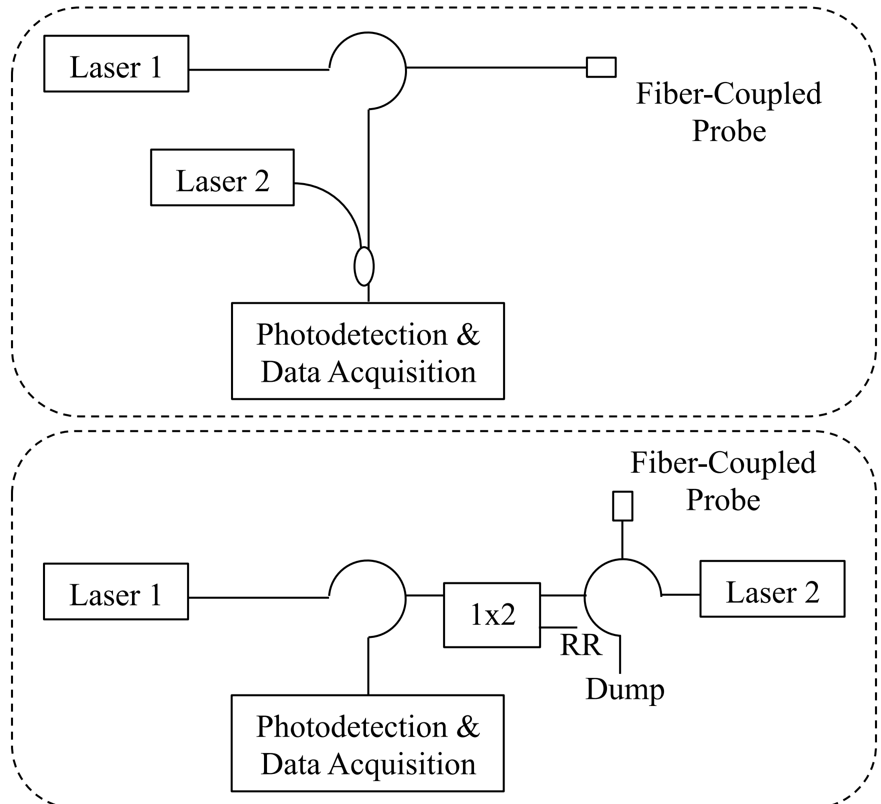
Background:
Variations in Architecture

- Different architectures for combining measurement and reference lasers

Homodyne:



Heterodyne:



Architecture from D. Dolan, et al.

Background:
PDV Overview & Performance Summary

- PDV measures Doppler shifts induced by displacement along a beam axis *(Briggs, 2008; Dolan, 2009; Briggs, 2010)*
  - Does not measure a transversely moving angled surface, since individual surface facets do not impose Doppler shift… In other words, ***PDV does not directly measure position***
  - PDV is robust in the sense that measured beat frequencies always arise from the displacement of a scatterer along the beam axis, and not from lateral motion, tilt, etc.
- PDV is very good at (1) measuring a large range of velocities with relatively low signal strength, (2) while multiplexing, and (3) in a "plug and play" fashion
  - Though, PDV has difficulty measuring quickly changing slow velocities, as a consequence of fundamental tradeoffs between temporal and frequency resolution
- By way of contrast, VISAR is more complex to field, but can do extremely well at measuring quickly changing slow velocities
  - Note, VISAR uses an intensity measurement, and PDV utilizes frequency measurement
- The remainder of this talk will focus on PDV specifically…

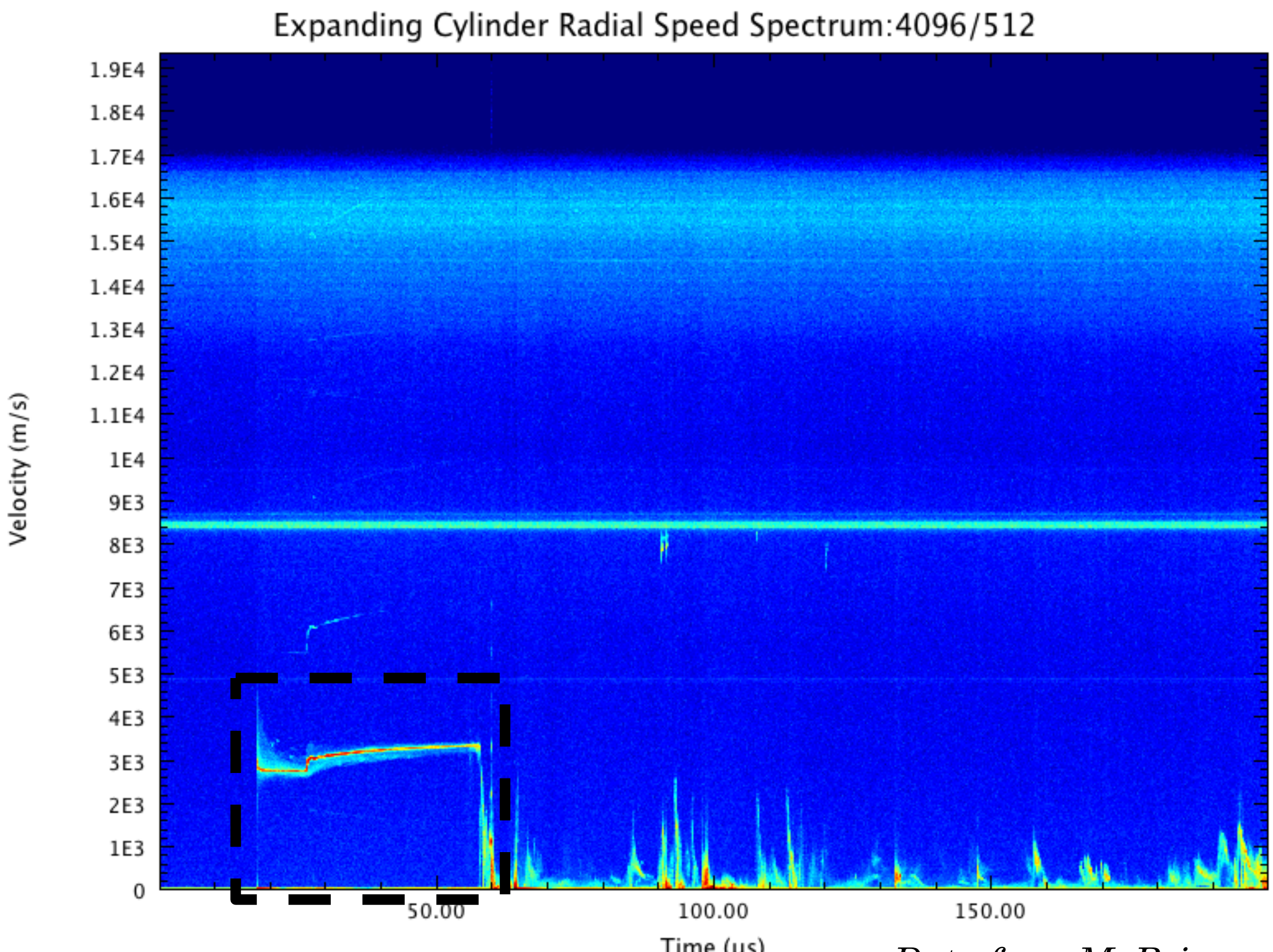
System Level Developments: MPDV Overview

- Multiplexed PDV or MPDV; 32 channels recorded on a 4-channel digitizer, as opposed to 4 un-multiplexed or 8 (1x2) time-domain multiplexed channels
  - Multiplexing may be done in the time and frequency domains
  - This technique was acknowledged with a R&D 100 award in 2012 *(www.rdmag.com)*
  - MPDV decreases the cost associated with achieving large channel counts

Photo from D. Holtkamp

System Level Developments: MPDV Overview

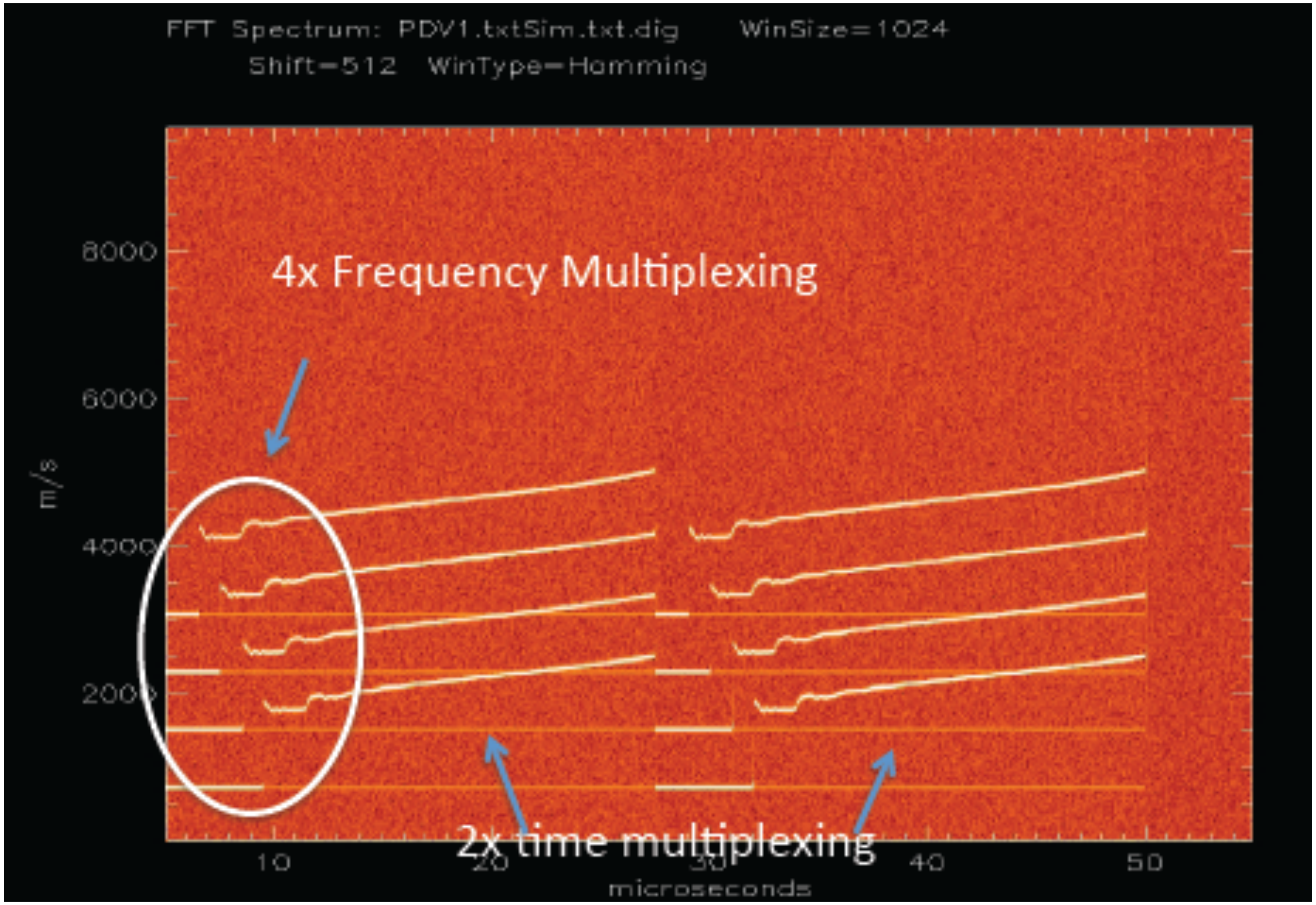
- MPDV is capable of returning a data richness that was not previously attainable
  - Rich velocity data in terms of spatial coverage of a dynamic event
  - Makes good use of resources, in terms of bandwidth and record length



Data from M. Briggs

System Level Developments: MPDV Overview

- Better use of bandwidth and memory resources:



Results from E. Daykin

System Level Developments: MPDV Architecture

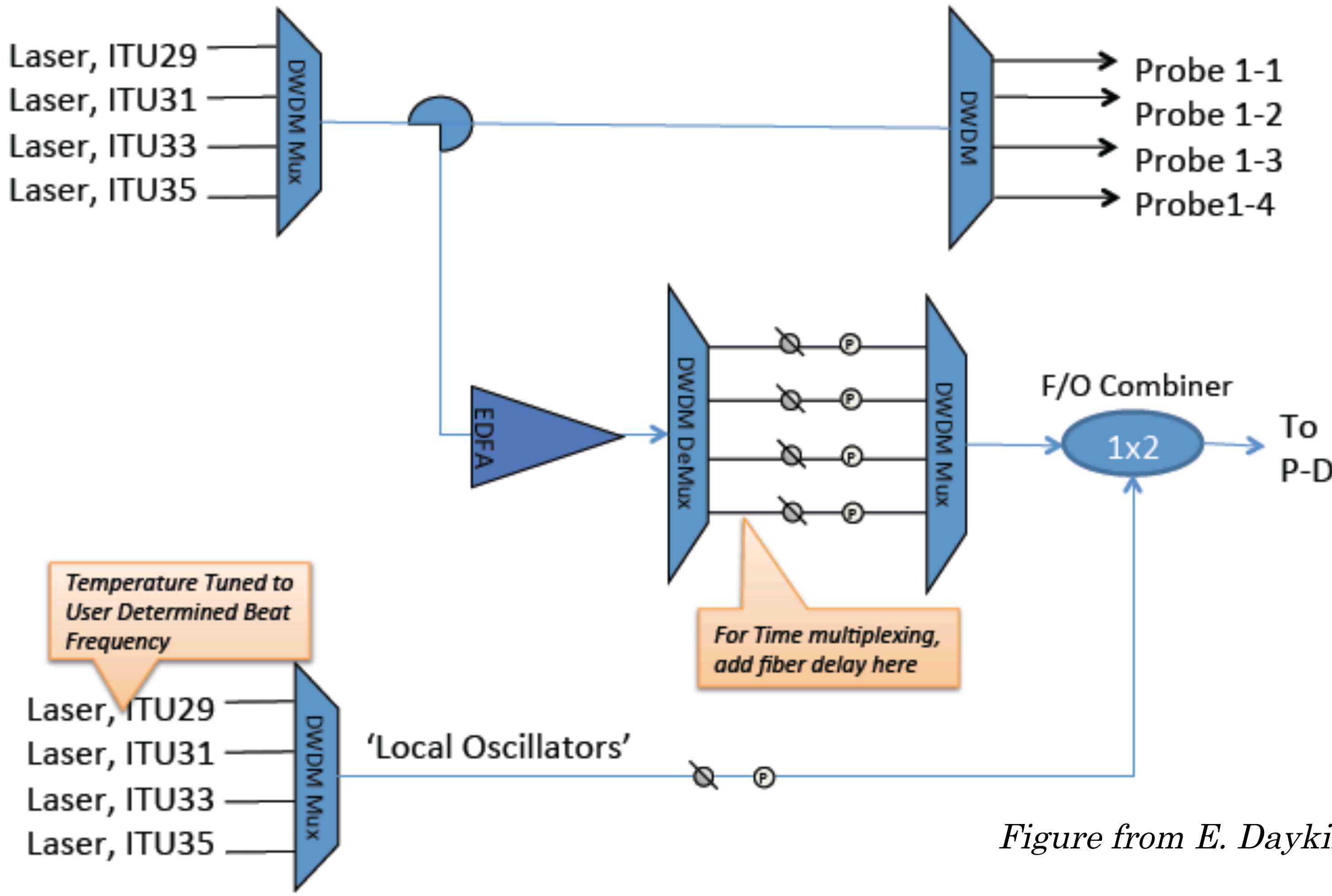


Figure from E. Daykin

System Level Developments: MPDV Probe Design

- MPDV success is largely supported by probe designs that enable dense packing *(Frogget, 2012)*
  - Tremendous engineering efforts at NSTec resulted in working probe designs whose reliability, field of view, and performance enabled groundbreaking work
  - Precise mapping to known locations on a dynamic surface

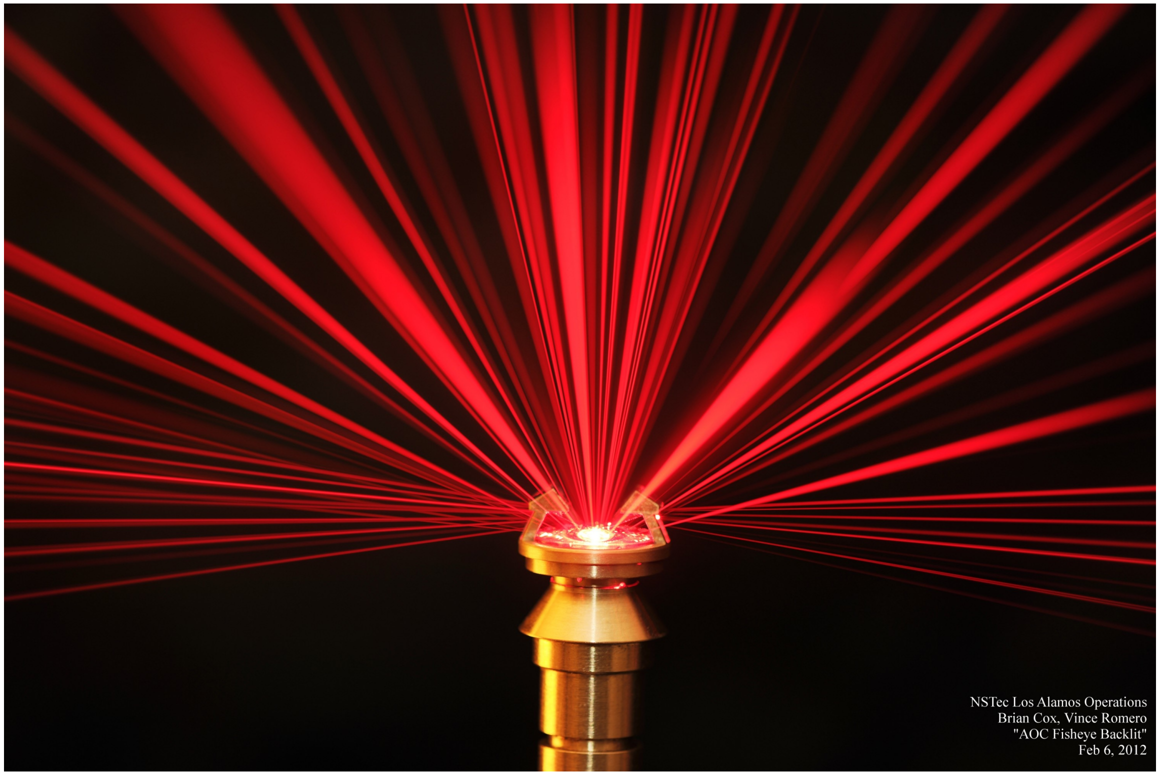


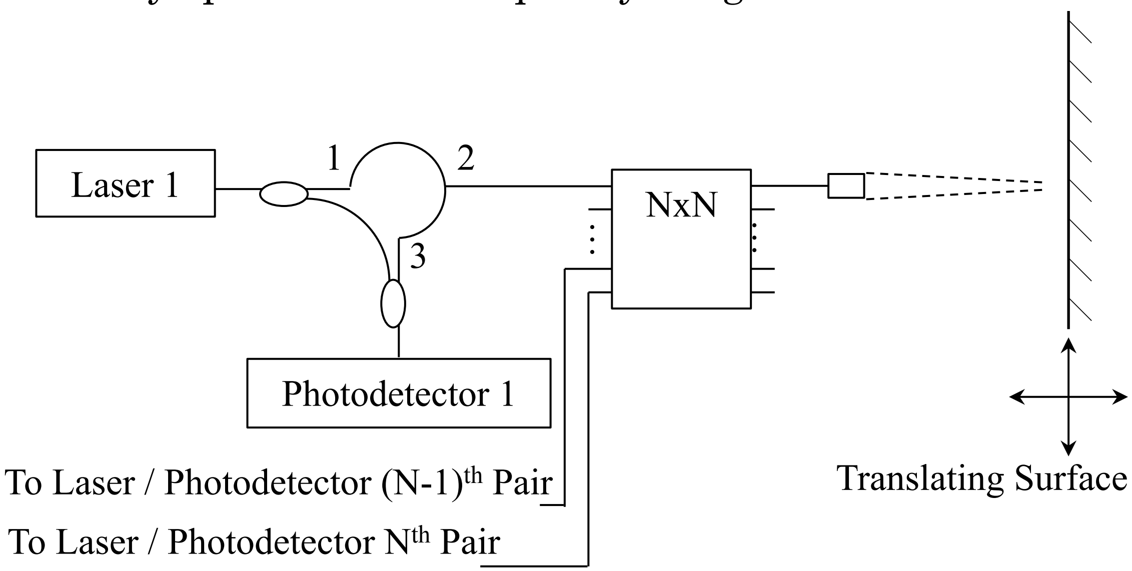
Photo from B. Cox & V. Romero

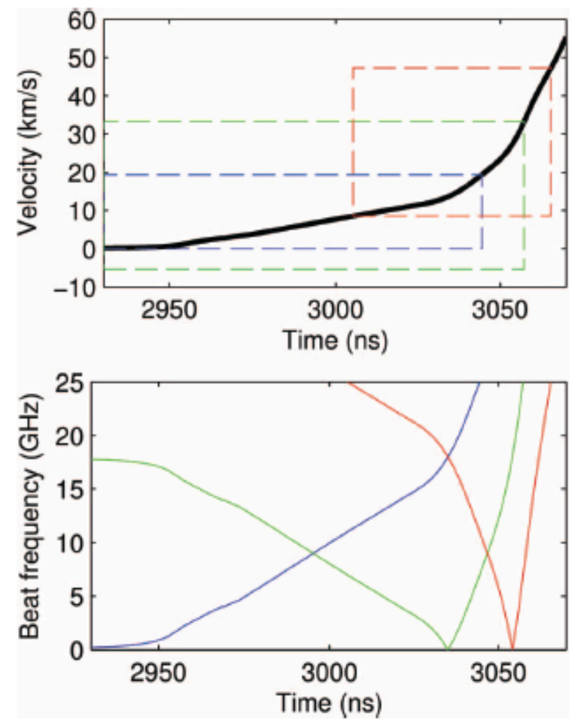
System Level Developments: MPDV Ongoing Work & Future Improvements

- MPDV reduces the dynamic range per channel and introduces challenges to the velocity extraction process *(Daykin, 2012)*
  - Dynamic range is improved by reducing circulator bleed-through, increasing the EDFA amplification of illuminating beams, and improving probe efficiency
  - Consider the advantages of long record lengths and multiplexing in the time-domain, easing the bandwidth/dynamic range restrictions on frequency multiplexing
  - On a related note: Some surface geometries are conducive to cross-talk between probes
- An increase in channels demands expedient pre-test diagnostics
  - Automatic switching, data-logging, and data-transfer throughout test assembly is necessary for enabling large channel-counts
  - These efforts are underway at NSTec, LANL, and LLNL
- With larger and larger data sets, there is also room to streamline data analysis (more on this later)

System Level Developments: Leapfrogging for Increased Velocity Range

- Leapfrogging is a technique that uses multiple lasers for heterodyning with the measured signal, and D. Dolan et al. *(Dolan, 2013)* recently resolved imploding cylinder velocities from rest up to 43 mm/μs
  - System architecture is essentially multiple photodetector paths, each with its own reference beam, and the reference beam wavelengths are designed in such a way that they span a broad frequency range





Results from D. Dolan, et al.

Data Analysis Developments: Expediting MPDV Feature Extraction

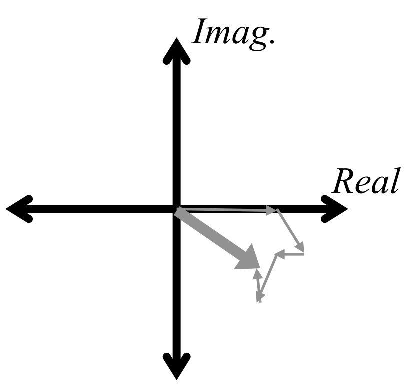
- The increase in channel count by itself increases the amount of work that goes into MPDV data analysis
  - One LANL hydro shot with MPDV generates an amount of velocimetry data that used to take a couple years to accumulate
  - This motivates the development of increasingly sophisticated feature extraction algorithms, even in the case of simple frequency-to-velocity extractions, based purely on the increase in channel count
  - This also motivates establishing an organized framework for relating a tests design, build, and data
- NSTec, LANL, and SNL each have their own data analysis programs
  - One approach would be automating the gathering of metrology and incorporating it throughout the build and into the analysis, and streamlining the analysis through methods of cutting and pasting baselines, regions of interest, etc. for velocity extraction

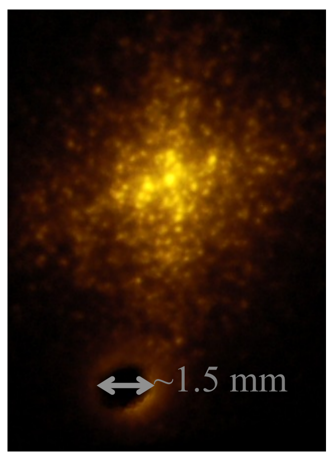
Data Analysis Developments: Accuracy & Precision Studies

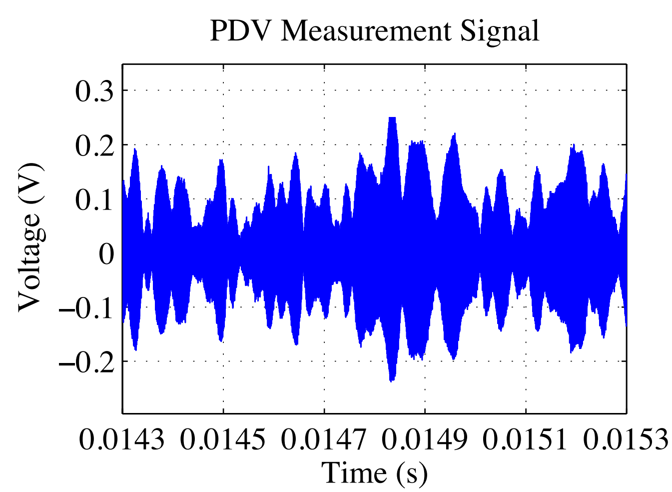
- Accuracy and precision studies by D. Dolan *(Dolan, 2010)*, where a Monte Carlo approach was used to simulate uncertainty and quantify its effects on the Fourier transform based velocity extraction process
  - Precision, as opposed to accuracy, was shown to dominate performance at non-low frequencies
    - Sampling rate, signal duration, and signal to noise ratio were shown to govern the ultimate precision
  - At low frequencies, the discrete Fourier transform is biased toward zero
    - This is a direct consequence non-periodic signal elements (e.g., partial interferometer fringes) in the DFT algorithm (which assumes periodicity)
    - This in and of itself is a motivation for using frequency-upshift PDV
- Experiments by M. Briggs et al. *(Briggs, 2011)* split a single probe's signal eight times and addressed precision in the case of non-constant velocity
  - A Gaussian fit was used to extract the velocity from the spectrogram, and the results suggest that its second moment is a reasonably conservative estimate of accuracy

Speckle Dynamics: Background

- Speckle originates from facets, which generate constructive and destructive interference in the reflection from a diffuse surface
- We recently demonstrated that laser speckle behavior in a PDV signal has utility in measuring a surface's transverse motion in some applications *(Moro, 2013)*
  - Historically, signal dropouts caused by speckle have been viewed as a hindrance to PDV
  - Perhaps, speckle-induce dynamics can be employed for extracting information about the surface's dynamic response, without otherwise requiring system-level changes

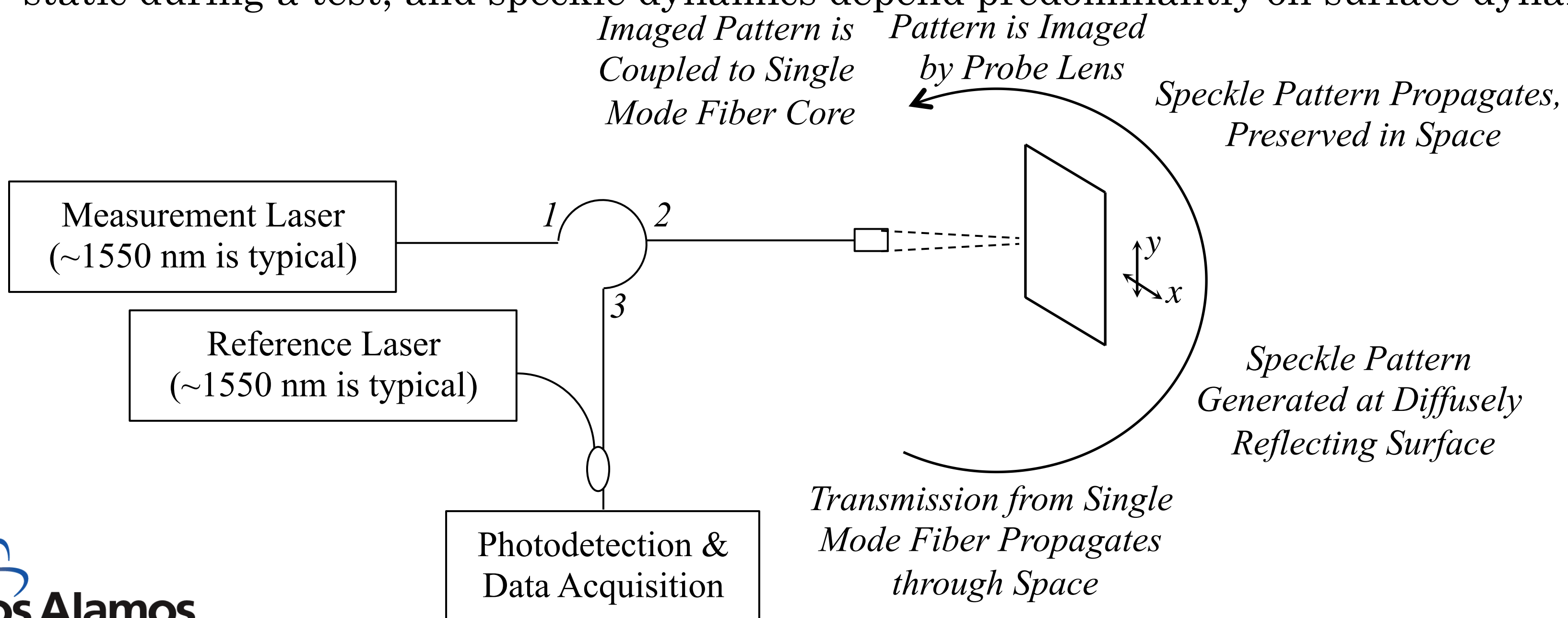






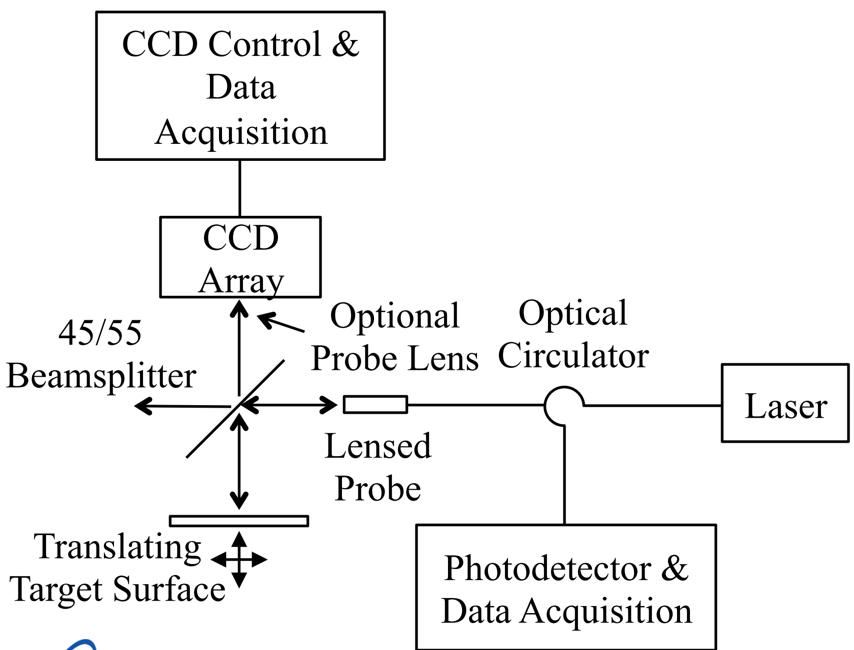
Speckle Dynamics:
Origin and Nature of Speckle in PDV

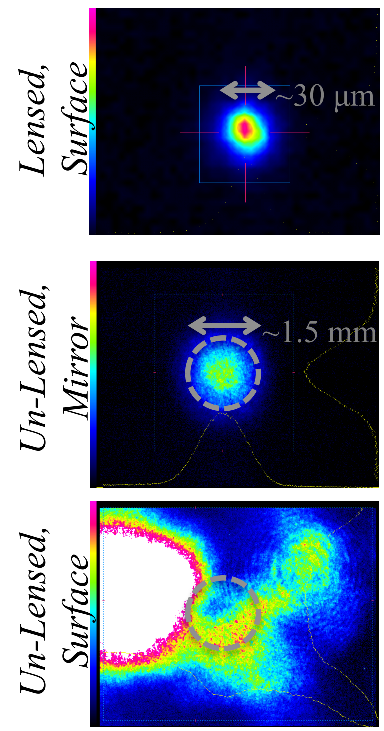
- The speckle pattern originates at the surface and propagates through space
- The pattern is imaged by the probe's lens and is integrated over the single mode fiber's core, where it is reduced to a single, time-varying amplitude/phase pair
  - This mixes with the reference laser, yielding effects on the measurement signal
  - Optics may superimpose their own phase onto the pattern, but these are generally static during a test, and speckle dynamics depend predominantly on surface dynamics

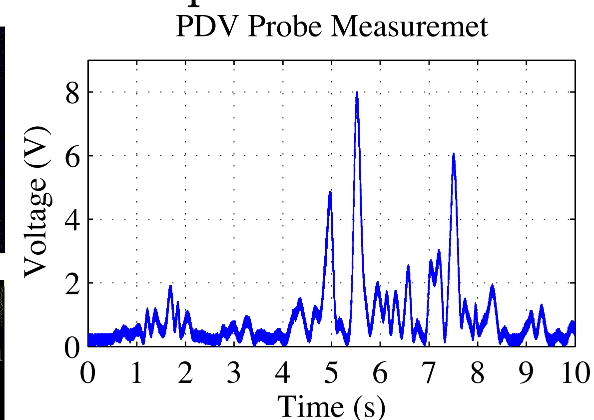


Speckle Dynamics:
Measurement of Speckle Properties

- An understanding of the relationship between speckle dynamics and surface dynamics is critical for feature extraction
- This test related two copies of the speckle patterns propagating through space: one mapping onto a CCD array and the other imaging to a PDV probe

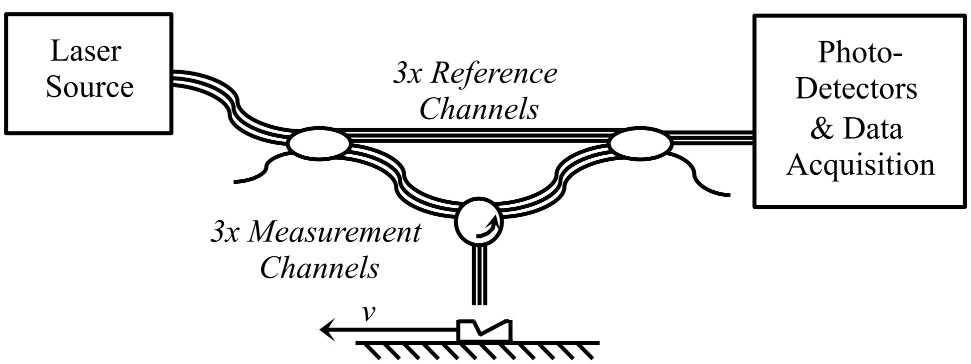


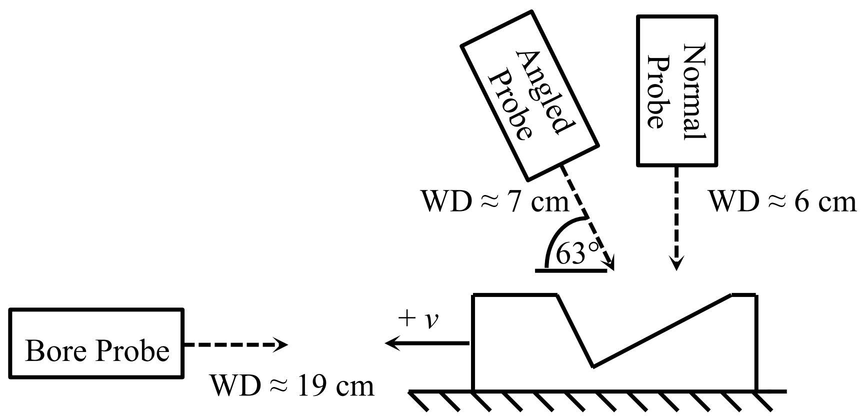




Speckle Dynamics:
Application to Speed Measurement

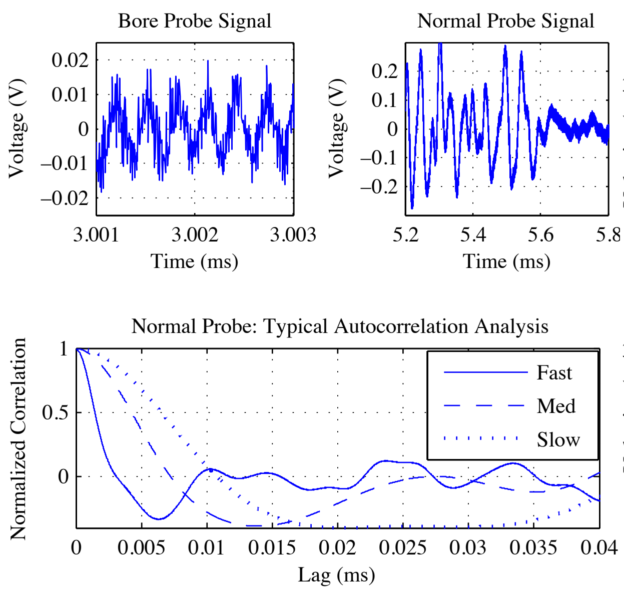
- Based on tests that we ran in the last several months, we demonstrated that a PDV probe from a typical setup (upshifted or standard) can measure surface motion transverse to the optical beam *(Moro, 2013)*
- Therefore, a probe that is angled with respect to the surface's trajectory may simultaneously measure motion along the beam axis (using standard PDV frequency analysis) and transverse to the beam (using speckle analysis)

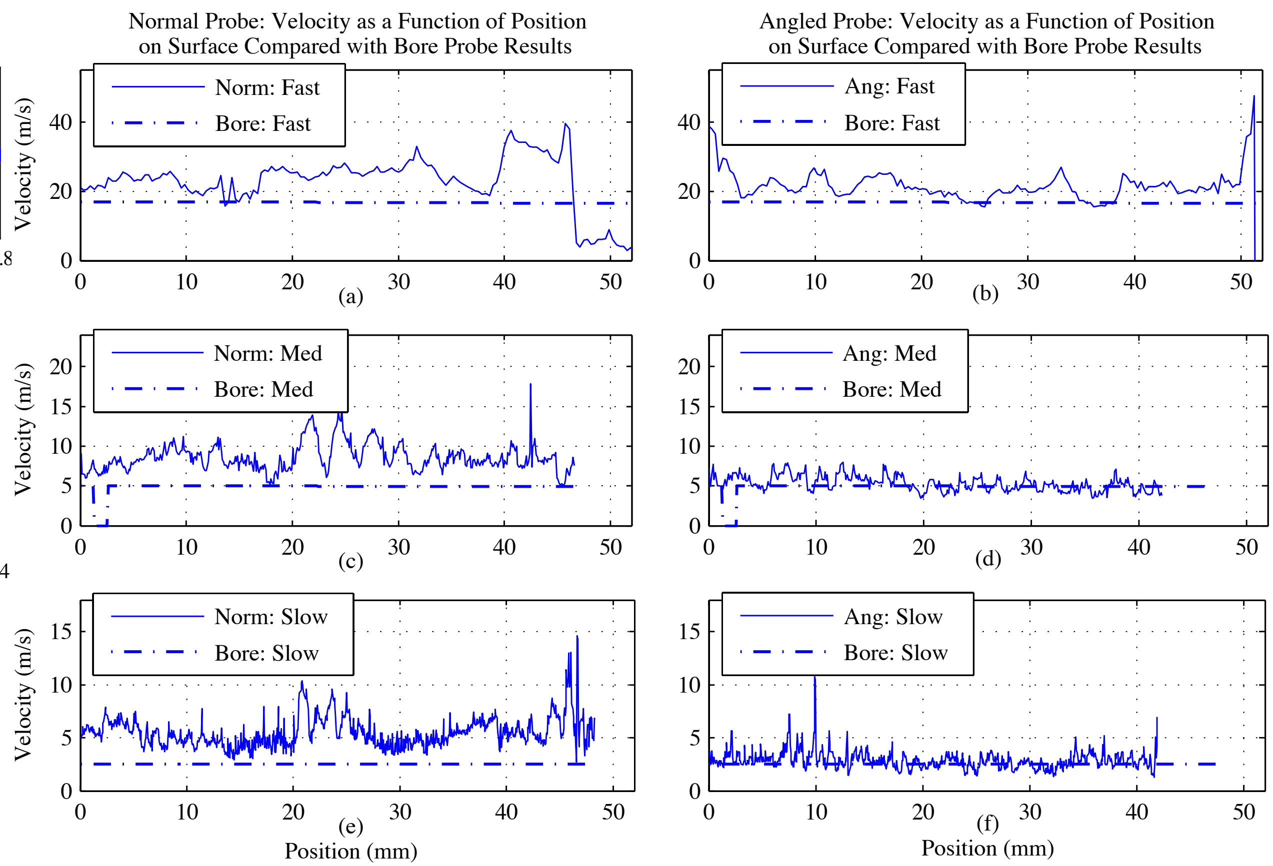




Speckle Dynamics: Feature Extraction

- Coherence times, calculated using the autocorrelation function, have been related to transverse surface velocities using $|v_{S\perp}| = w_0 / \tau_C$

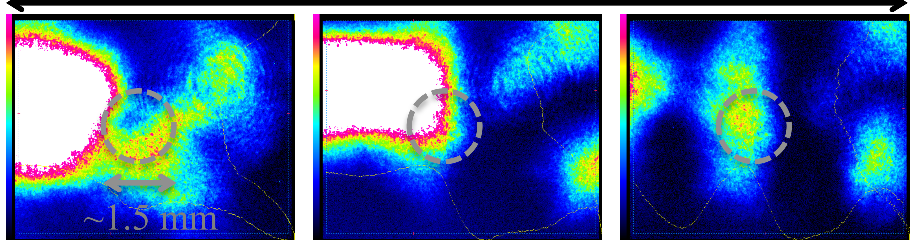




Speckle Dynamics:
Improved Feature Extraction

- Further research in this area is motivated by, what are likely, more complicated relationships between measured speckle dynamics and surface dynamics
  - Time-scales, which are treated statistically, depend on the dynamic nature of the speckle pattern
  - Spatial dimensions, which are treated statistically, depend on the true speckle size (not its average) and on the trajectory of a speckle across the measurement aperture

100 μm Surface Translation: Demonstrates Boiling and Translation



Speckle Velocity:

$$|v_{S\perp}| = \frac{w_0}{\tau_C} \propto \frac{D_S}{\tau_C}$$

Depends on actual speckle size (D_S)

Depends on where speckle crosses aperture
Depends on boiling versus translation (τ_C)

Speckle Size:

$$\overline{D_S} \approx \frac{1.2\lambda z}{D_L}$$

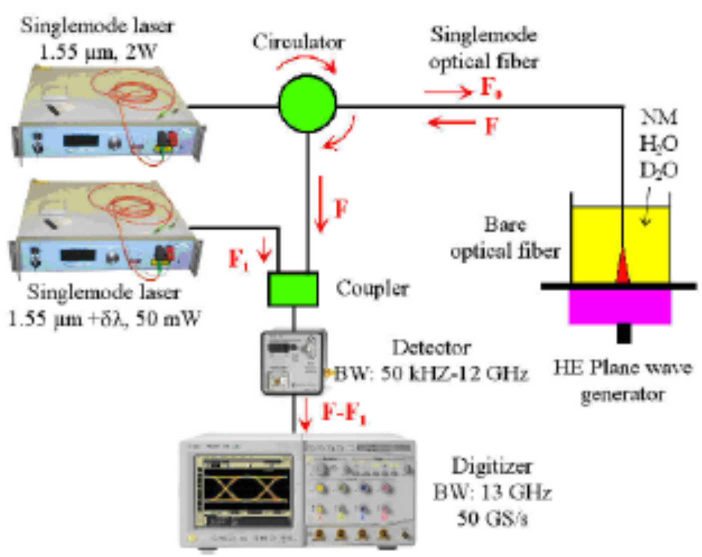
$\overline{D_S} \approx 1.5mm$ for λ=1550 nm, z=75mm, and D_L=100 μm

New Applications: Optical Fiber "Pins"

- Mike Shinas (LANL) has developed optical fiber "pins" for sub-nanosecond timing of shock arrival *(Shinas, 2013)*
  - Simultaneously reveals TOA and frequency content as shockwave interacts with fiber
    - Measures the arrival of a shockwave at an optical fiber
    - Fibers coated with aluminum performed the best of those tested
  - Timing capability is sub-nanosecond, demonstrated with upshift PDV
    - For more details, see Mike's talk on Thursday of this week

New Applications:
Transparent Media

- Measurement in a transparent medium where simultaneous or sequential events may be accessible *(Mercier, 2012)*
  - Shockwave velocity, measured directly in the medium
  - Shockwave velocity measured as it interacts with the immersed optical fiber
  - Meanwhile, the free surface velocity of the transparent medium is also measured



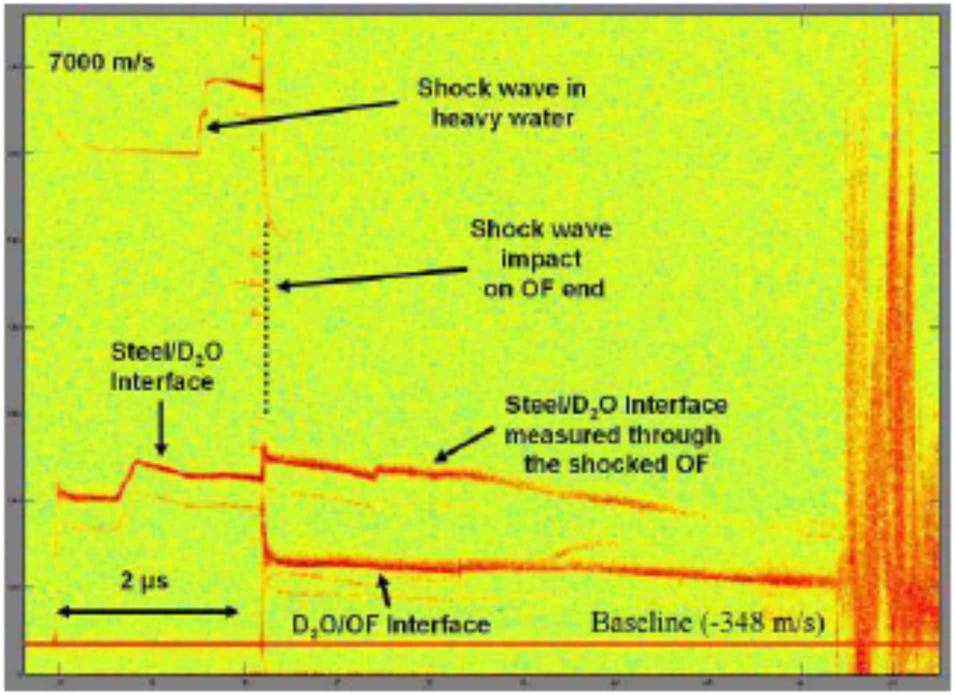
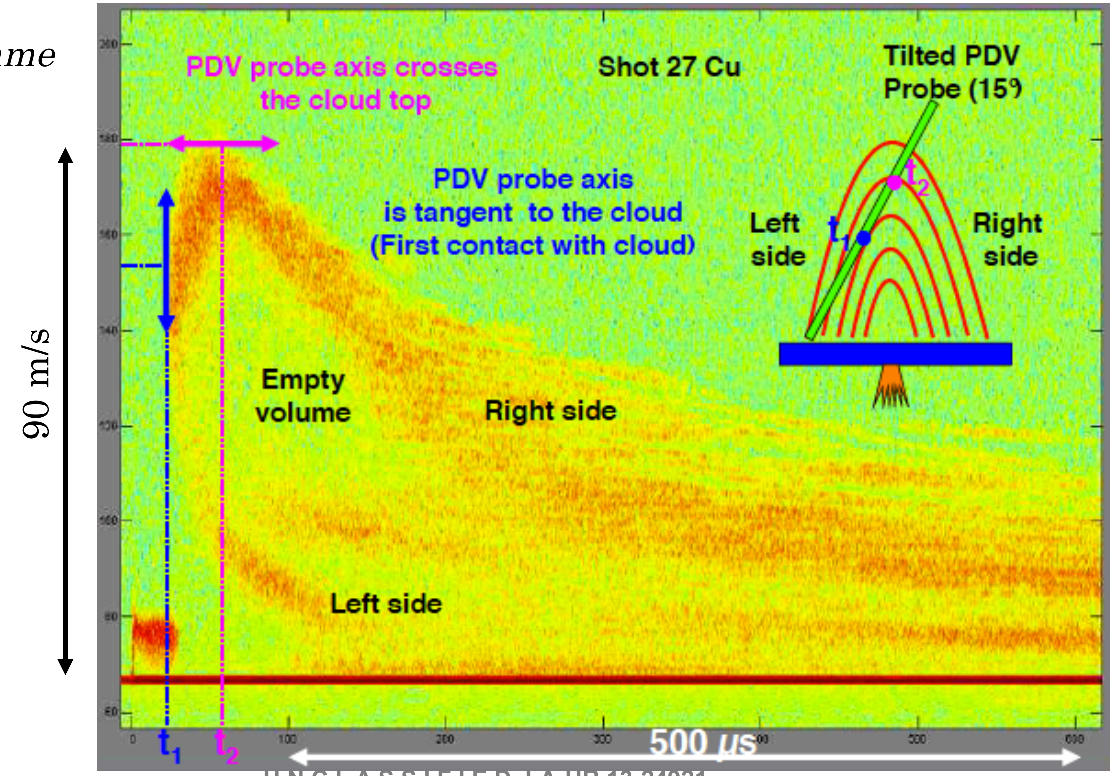


Diagram and Results from P. Mercier

New Applications:
Ejected Particles and Cloud Shape

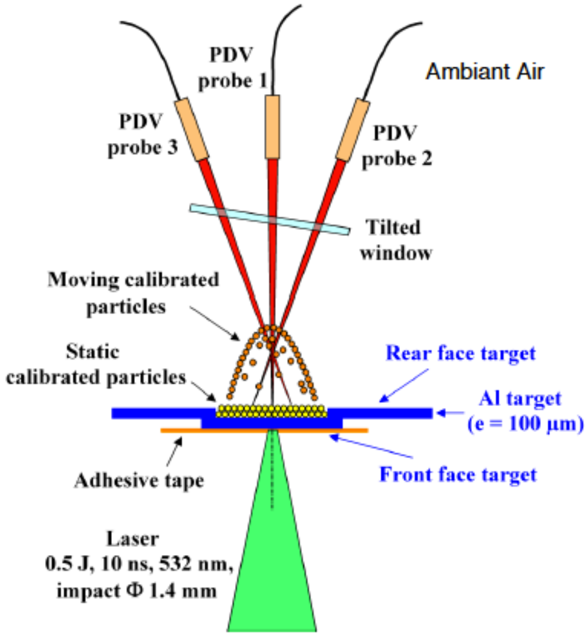
- Using tilted probes, the cloud's structure may provide particle densification or rarefaction information *(Prudhomme, 2012)*
  - A velocity range may be accessible, depending on the cloud's depth-dependent opacity
  - The particle origin's free surface velocity is sometimes accessible through the cloud

Results from G. Prudhomme



New Applications:
Ejected Particles and Particle Size

- PDV probes measure calibrated particles that are ejected from a surface, providing insight into distinct particle trajectories *(Prudhomme, 2012)*
  - There is promise relating extracted velocity histories to particle size, using a non-linear optimization technique to solve for system parameters



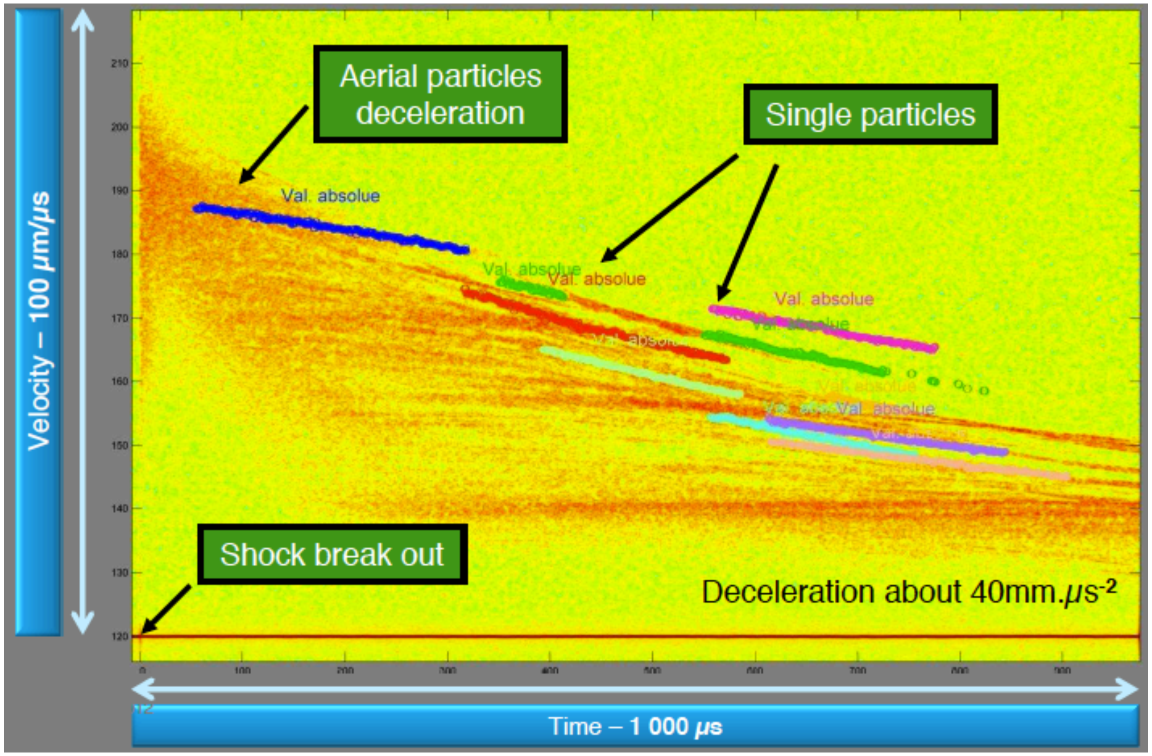
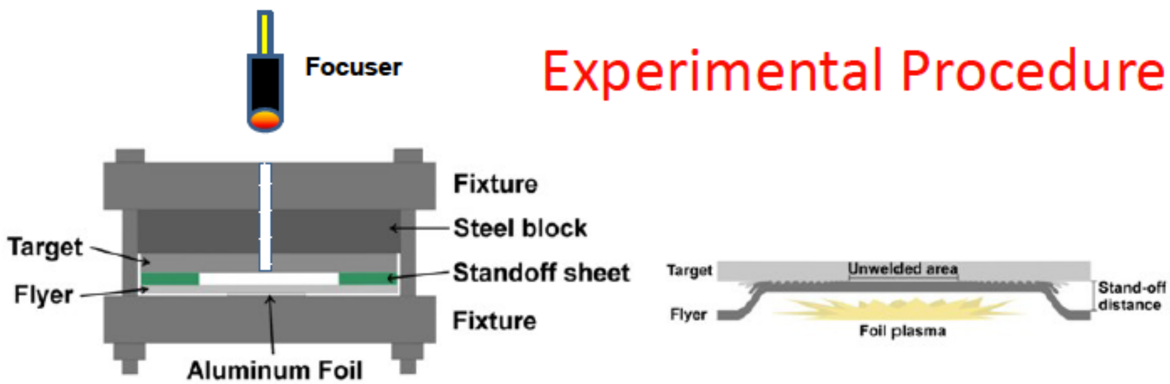


Diagram and Results from G. Prudhomme

New Applications:
Measurement of Slow Velocities

- Applications at relatively slow velocities includes collision welding *(Vivek, 2013)*
  - PDV serves as a diagnostic for monitoring whether or not impact velocities are within an acceptable window for producing a strong weld
  - Flyer velocities are on the order of 300-600 m/s
- Other mechanical vibrations applications



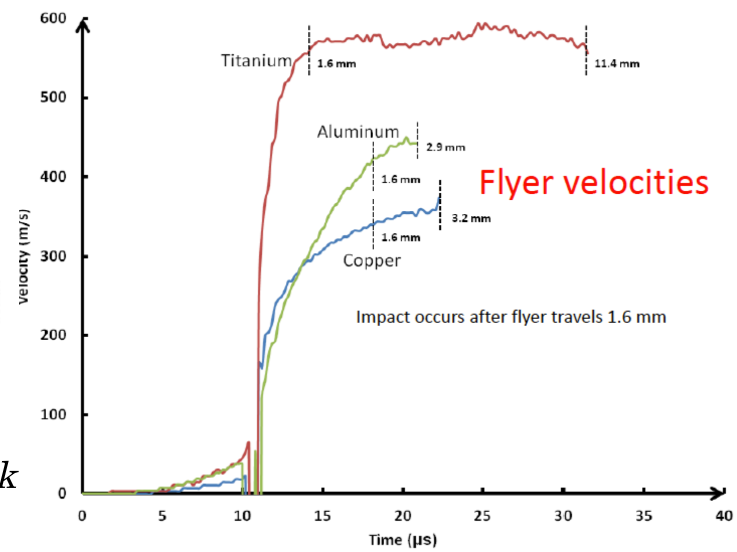


Diagram and Results from A. Vivek

New Applications:
Trajectory Reconstruction

- Accounting for transverse velocity component directly, or measuring absolute position directly
  - Can be of critical importance if material position is required, since a transversely moving angled surface will introduce errors to the position integrated from velocity
  - Matt Briggs is presenting on Thursday of this week on a time-of-flight approach for measuring surface displacement *(Briggs, 2013)*
- Discerning additional information from features in the PDV signal
  - What features are embedded in the signal and how to we best exploit them?
  - This may include, but is almost certainly not limited to, speckle effects

Conclusions & Ongoing Challenges for PDV: System Level

- MPDV, and related system level developments, are creating new opportunities
  - Increases in ***both*** usage and channel counts are driving a need to systematically, and automatically (when possible) process and analyze data
    - This includes but is not limited to expedited feature extraction
- Leapfrogging demonstrates (as do other creative architectures) versatility in using PDV for a range of applications
- There is always a demand for increased oscilloscope resolution and bandwidth
  - Related directly to multiplexing limits of MPDV systems, as well as velocity extraction capabilities of (all) PDV systems
  - This is coupled to efficient feature extraction for determining velocity history

Conclusions & Ongoing Challenges for PDV: Data Analysis & Phenomenology

- As PDV and MPDV gain steam, they drive an increase in capability and data fidelity that enables us to answer new questions
  - Questions pertaining to surface response to loading and the interferometer's response to such phenomena
    - Failure and melt
    - Angular reflectivity variations, measured by the scattering of the light at the free surface, may be connected to surface melting (CEA) or surface fracture
- Either (1) absolute, optical measurement of position or (2) measurement of transverse velocity, to account for transverse motion of an inclined surface and better reconstruct surface trajectory
- Signal dropouts (e.g., speckle diversity), and/or better understanding of relationship between speckle dynamics and surface dynamics

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Questions?