SAND2008-6036C

Three-phase velocimetry of material response to pulsed radiation

PDV workshop

September 3-4, 2008

Part I: Three-phase PDV analysis (Daniel H. Dolan)

Part II: Thermo-mechanical examples (Scott C. Jones)

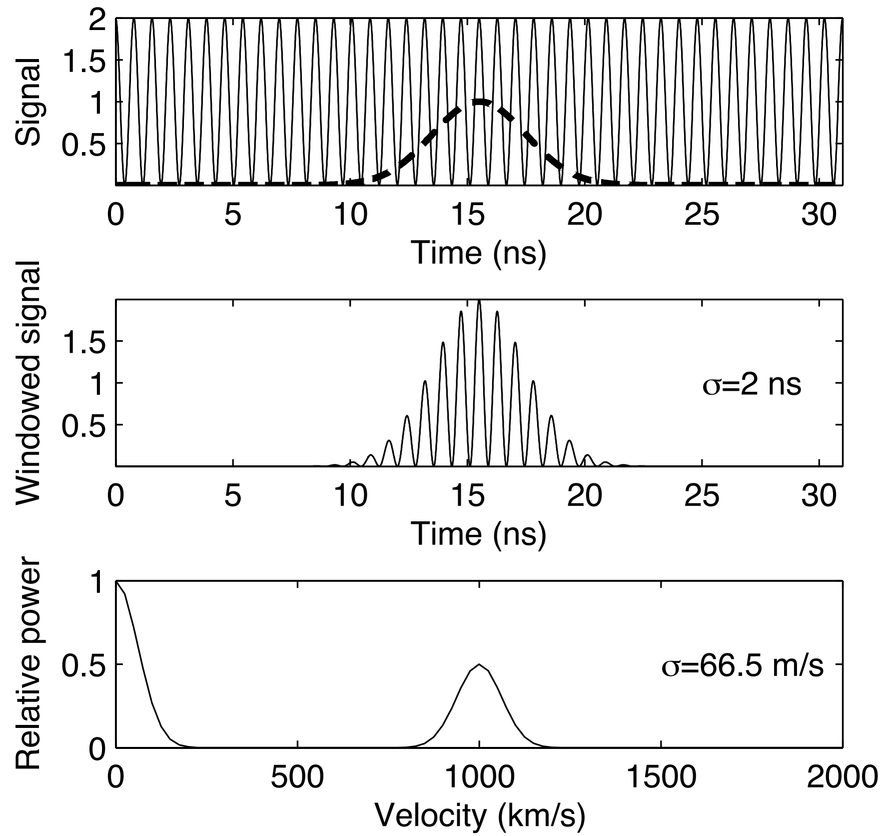
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

When is standard PDV insufficient?

- **Uncertainty principle**

$$\frac{\delta v}{v} > \frac{1}{4\pi}\frac{T_b}{\tau} \qquad \left(T_b = \frac{\lambda_0}{2v}\right)$$

- **Events faster than the beat frequency**
  - **Problem particularly bad at low velocities (775 ns @ 1 m/s)**
  - **What does frequency mean for changes faster than the period?**
    - **Acceleration or variable light conditions?**
  - **Changes during peaks/troughs**
- **Motion reversal**
  - **Standard PDV shows the same Doppler shift for motion in either direction**

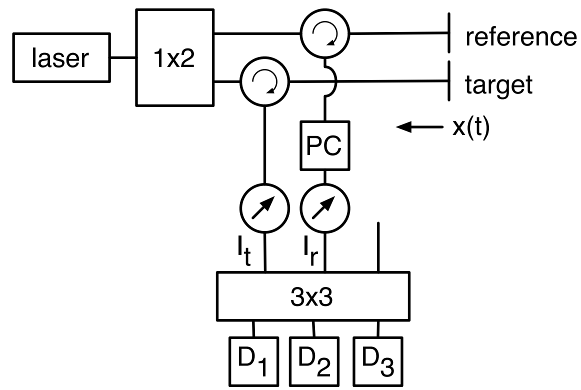


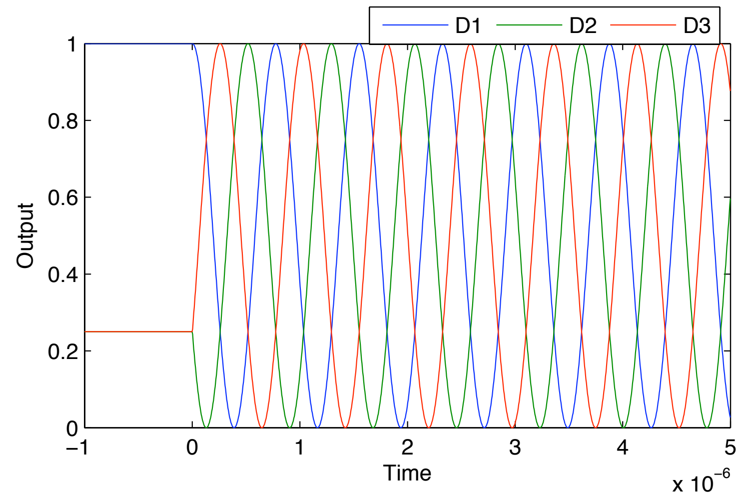
Three-phase PDV measurements

- **Phase-shifted signals produced with a 3x3 coupler**
  - **Three signals combined into a quadrature pair (push-pull approach)**
  - **Bad things (light variations, incoherent light) can be removed**

- **Caveats**
  - **Fringe shift proportional to displacement, not velocity**
  - **Depends on good <u>signal</u> contrast**
    - **Good optical contrast may not be necessary**

- **In some cases, only two phases are actually needed...but you really should record all three!**





$$f(t) = 2\frac{x(t) - x(t_i)}{\lambda_0}$$

Analysis summary

Convention:
D_2 leads D_1
D_3 lags D_1

- **Normalize the recorded signals**
  - **Ellipse characterization**
  - **Subtract ellipse center, divide by amplitude**

$$\tilde{D}_k = \frac{D_k - \bar{B}_k}{\bar{A}_k}$$

- **Generate quadrature signals**
  - **Determine balancing parameters**
  - **Combine normalized signals into quadrature pair**

$$D_y = \sqrt{3}\,(D_3 - D_2) \quad \text{(ideal PDV)}$$
$$= \sum_{k=1}^{3} g_k \tilde{D}_k \quad \text{(real PDV)}$$

$$D_x = 2D_1 - D_2 - D_3 \quad \text{(ideal PDV)}$$
$$= \sum_{k=1}^{3} h_k \tilde{D}_k \quad \text{(real PDV)}$$

- **Calculate fringe shift**

$$\tan\left[2\pi f(t)\right] = \frac{D_y(t)}{D_x(t)}$$

- **Differentiate to obtain velocity**
  - **Savitzky-Golay seems intuitive**
    - **Polynomial order**
    - **# points**

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Sandia's THRIVE program

- THRIVE: THRee Interferometer VElocimetry
  - Reduces three signals to a pair of perfect quadratures signals
  - Calculates fringe shift
  - Determines displacement and velocity (smoothing)
- Runs in MATLAB or as a Windows executable
  - Built in OS X, should operate in Linux (untested)
    - Currently requires MATLAB
  - Licensed for government use
- Documentation
  - User manual describes theory and program usage (SAND2008-3871)
  - Benchmark problems included
    - Velocity step
    - Velocity ramp
    - Velocity pulse

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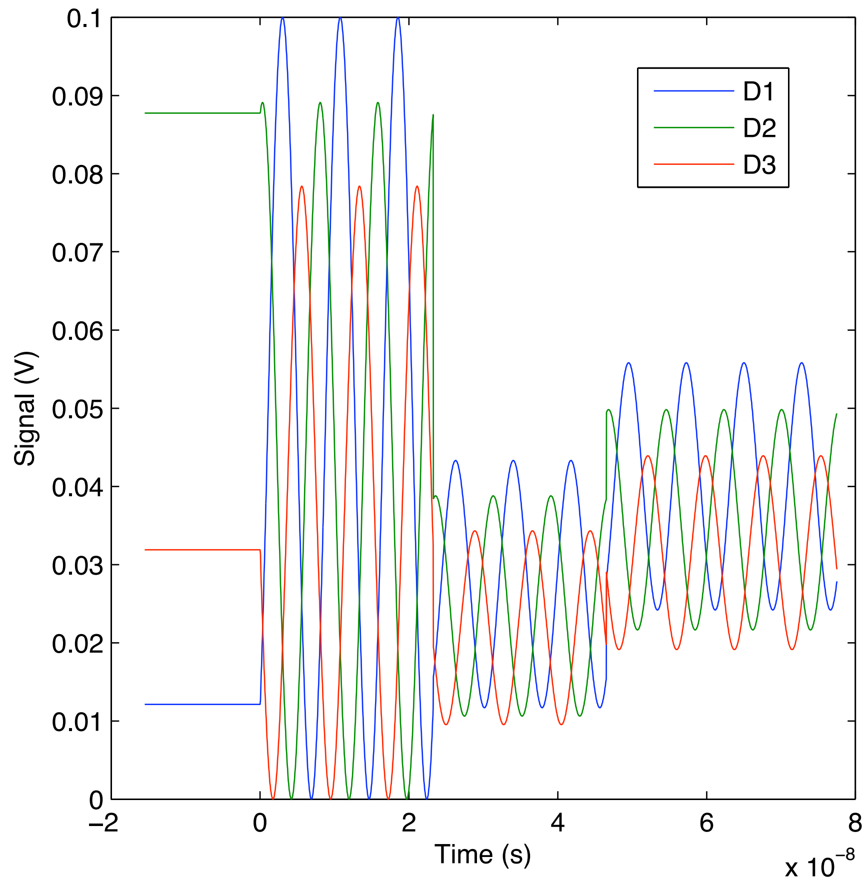
Example 1: velocity step (noise-free)

$$D_k = \frac{\eta I_C}{4}\left[1 + \rho_k \frac{I_T}{I_R} + 2\sqrt{\rho_k \frac{I_C}{I_R}} \cos\left(2\pi f(t) - \beta_k\right)\right] \qquad k = 1..3$$

- **Velocity jumps from 0 to 100 m/s (T=7.75 ns) at t=0**
  - **100X oversampling (Nyquist)**
- **DC coupled measurement**
  - **Scaled to ~100 mV**
- **Imperfect PDV system**
  - **D1-D2 shift is 125 degrees**
  - **100:98:96 optical split**
  - **100:90:80 sensitivity ratios**
- **Dynamic light conditions**
  - **Start with perfect optical contrast**
  - **Target light drop @ 3T to 10%**
  - **Incoherent emission @ 6T**



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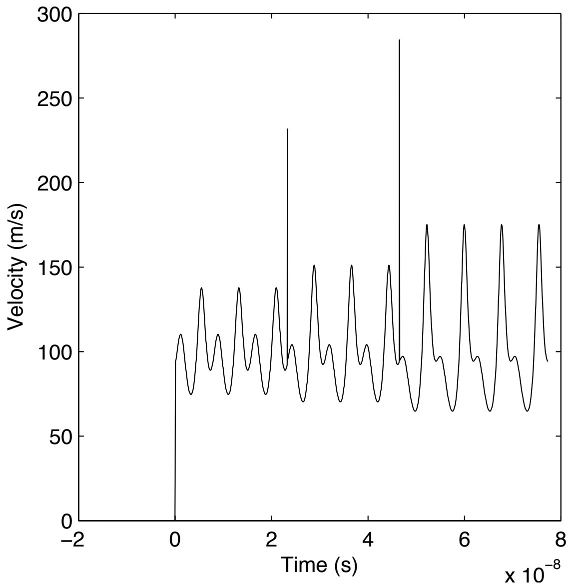
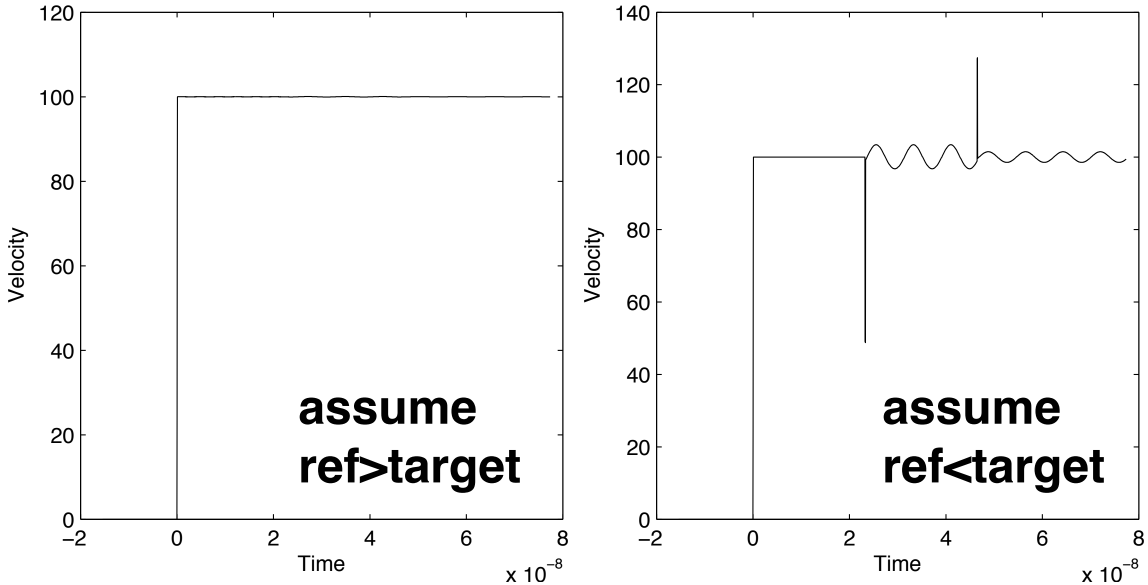
Example 1 results

Ideal analysis



Ellipse characterization



- **System defects cannot be ignored in three-phase analysis**
  - **Proper balancing handles <u>all</u> light conditions**
- **Ellipse characterization works...**
  - **with the right assumption(s) about target/reference light!**
- **Numerical precision eventually becomes a limiting factor**
  - **Better than 0.01-0.1% stability is difficult**

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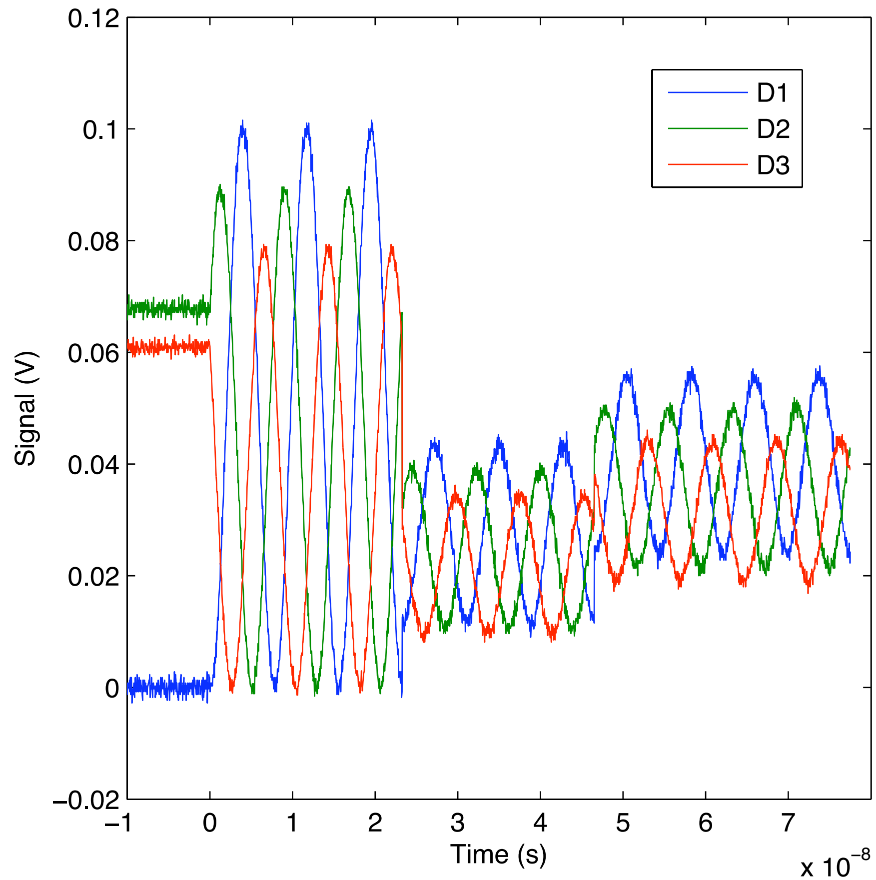
Example 2: velocity step (noise)

- Similar measurement conditions as previous example
- 1% signal noise added (relative to initial state)
- 8-bit digitization
  - Sampling over 10 divisions
  - Data restricted to 8 divisions
    - 1 div above, 1 div below
- Smoothing now plays a crucial role for velocity
  - Smoothing window should be kept below the beat period
    - 7.75 ns, in this example
  - Need for smoothing depends on SNR
    - Varies with light conditions



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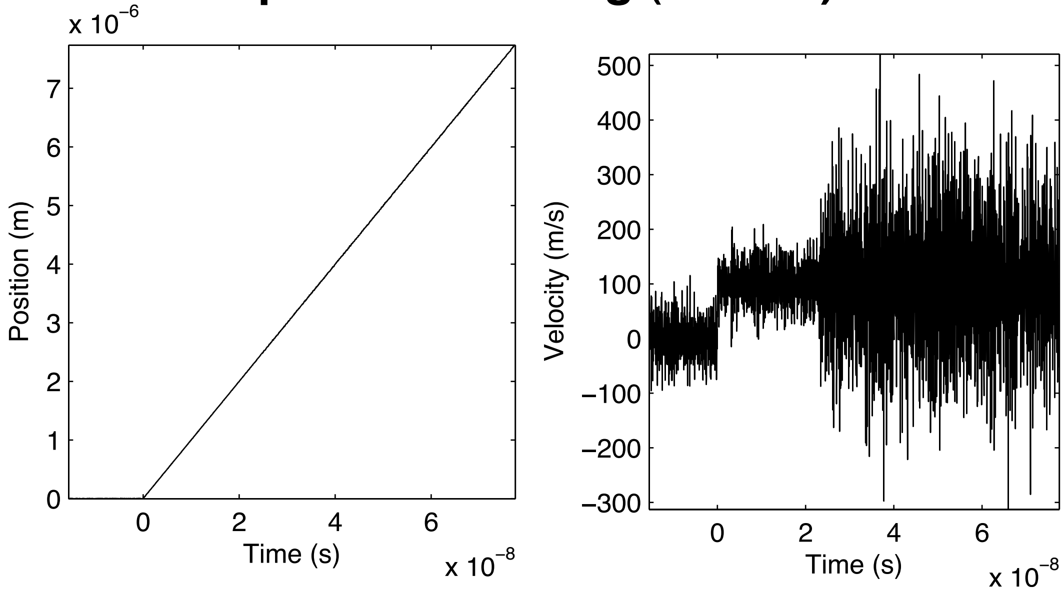
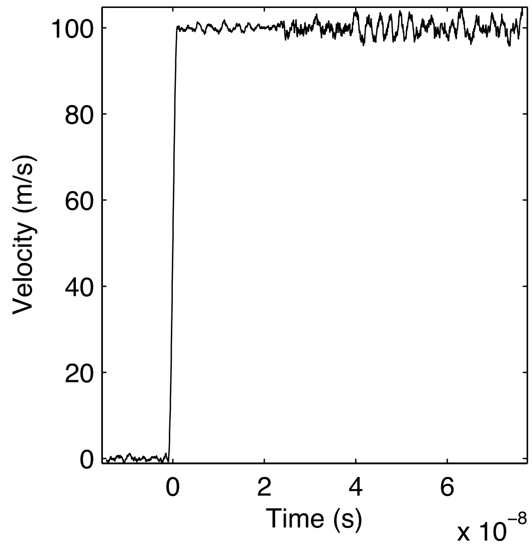
Example 2 results

3 point smoothing (default)



51 point smoothing (<2 ns)



- **Fringe shift and displacement are generally less noisy than the measured signals**
- **Velocity almost always requires smoothing in real measurements**
  - **Tradeoff between time and velocity resolution**
- **Warning: high contrast, noisy ellipses can lead to unphysical contrast estimates (DC coupling)**
  - **Use alternate parameter estimate, where possible**

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Summary

- Three-phase velocimetry measurements can be used to study events faster than the fringe period
  - Exact limits depend on noise, but 1/4-1/10 of a fringe period is feasible
- The analysis requires much more system characterization than standard PDV measurements
  - 3x3 coupler performance and relative detector sensitivities are important
  - Ellipse characterizations reveals most of the needed information
- Most three-phase reduction can be readily be performed with THRIVE
  - Available to government users
  - Feedback welcome

- And now for some real data...

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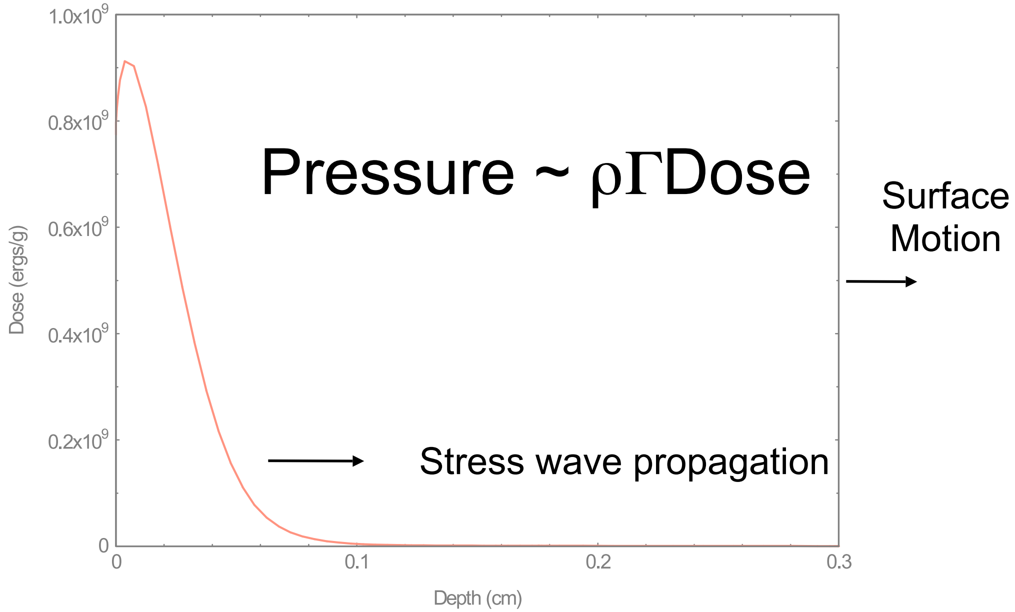
Part II

Thermo-Mechanical Effects
Examples of PDV/PDI Measurements

Thermo-mechanical Shock



Displacement interferometry is preferred for measurement of material response to pulsed radiation

- Radiation pulse stimulus imparts no momentum to sample
- Motion is not typically unidirectional
- Time windows of interest may run to hundreds of microseconds
- Velocity 'pulses' can be very narrow: ~ 10 ns or so

For our studies, velocities are nonuniform and small (peak values as small as a few m/s)

Peak displacements: fraction of one micron to several microns

Required VISAR delays (τ) for 'one-fringe' precision are impractical (532 nm air delay)

Validity of FT for extracting velocity unclear – nonuniform motion, reversals in velocity

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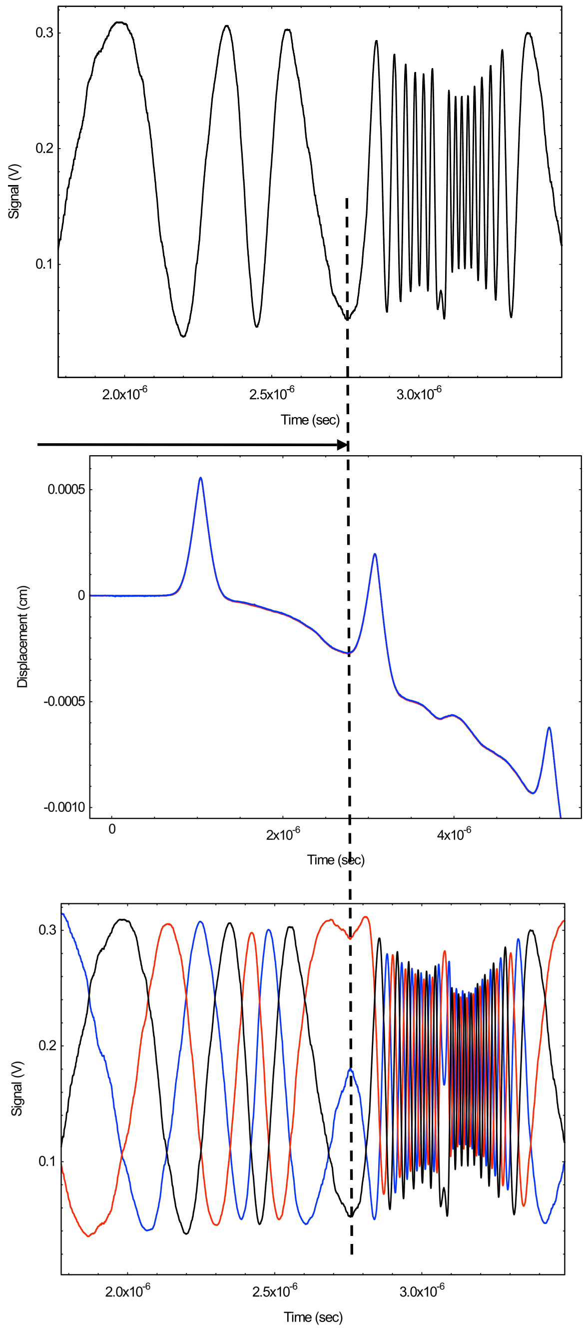
Motion is from a simple, ¼" thick aluminum disk in SPHINX electron beam – 10 ns

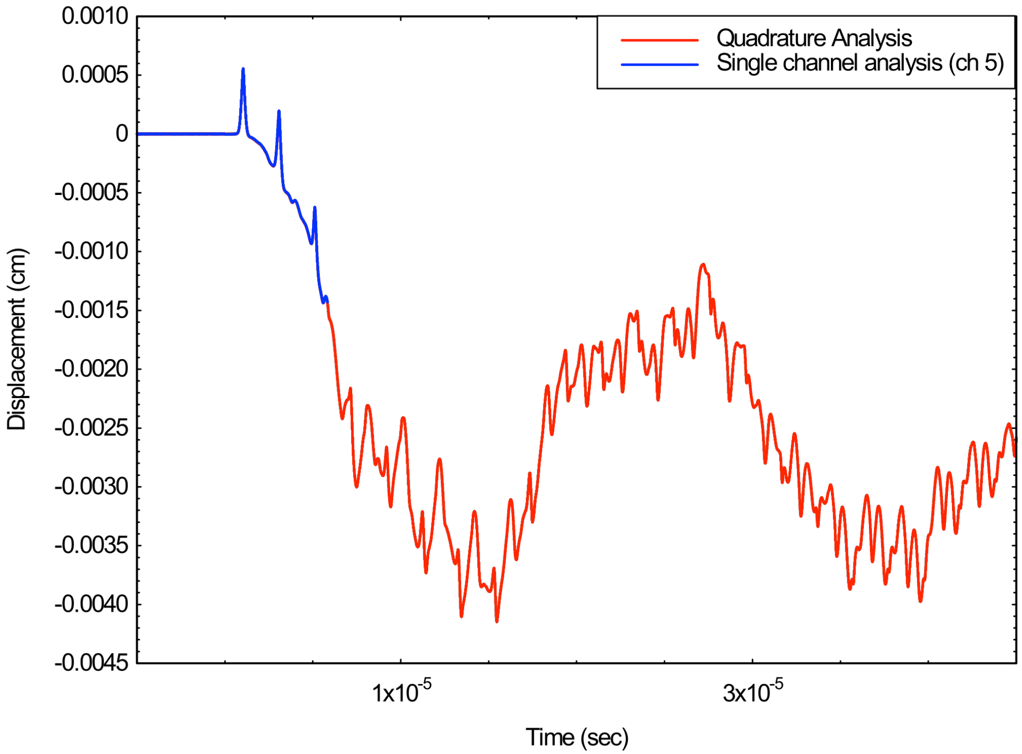
Reversal ambiguous in single channel record (top left), but clear in quadrature record (bottom left)

Automated analysis of long, complicated records is shown below.

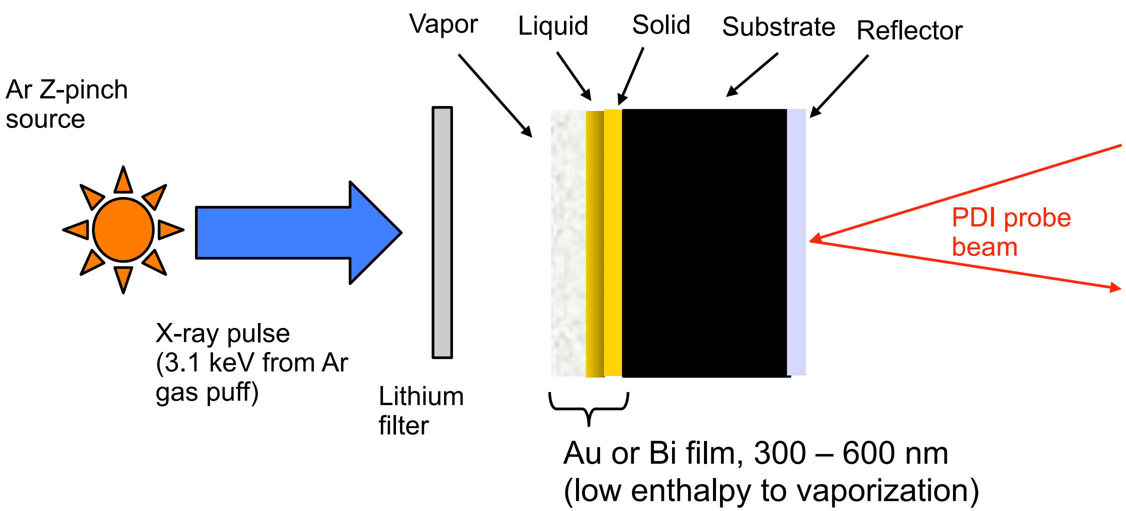
These two analyses are in excellent agreement in early part of record, but quadrature analysis is complete in a few seconds for entire record.

Reversal

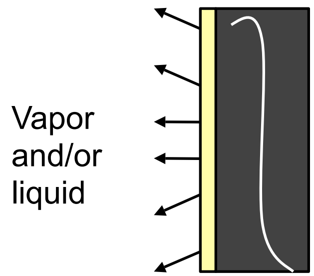




Impulse Measurement



Momentum of vaporized material imparts equal/opposite momentum to substrate (impulse)



The general case is complex in this study:
All three phases (vapor, liquid, solid) may exist on any shot, depending on energy fluence incident on sample.

Results will be challenging to duplicate in modeling.

AWE Collaborators: A. Sibley, A. Hughes, R. Burrell, N. Barnes

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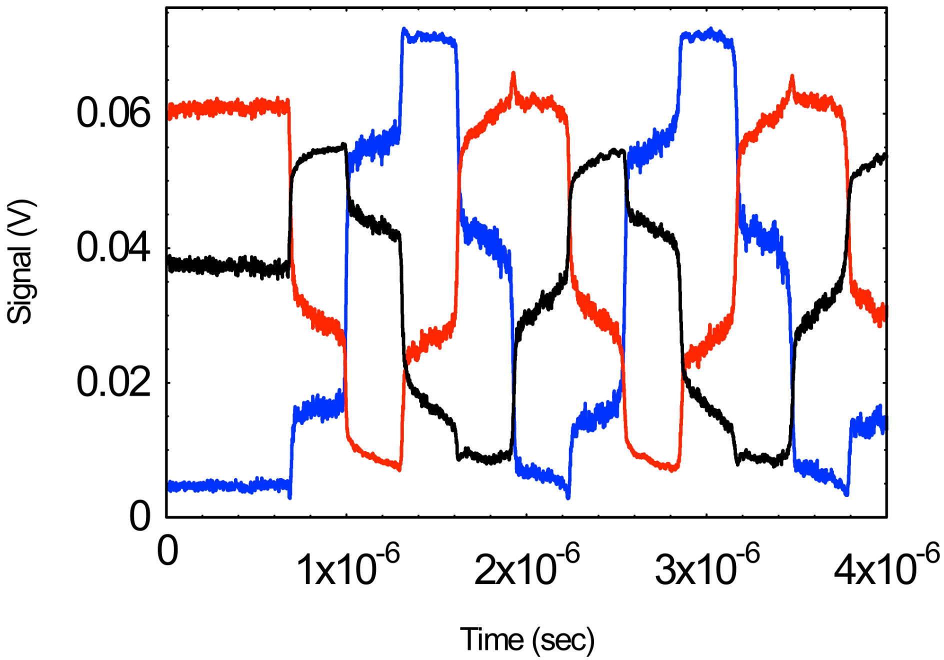
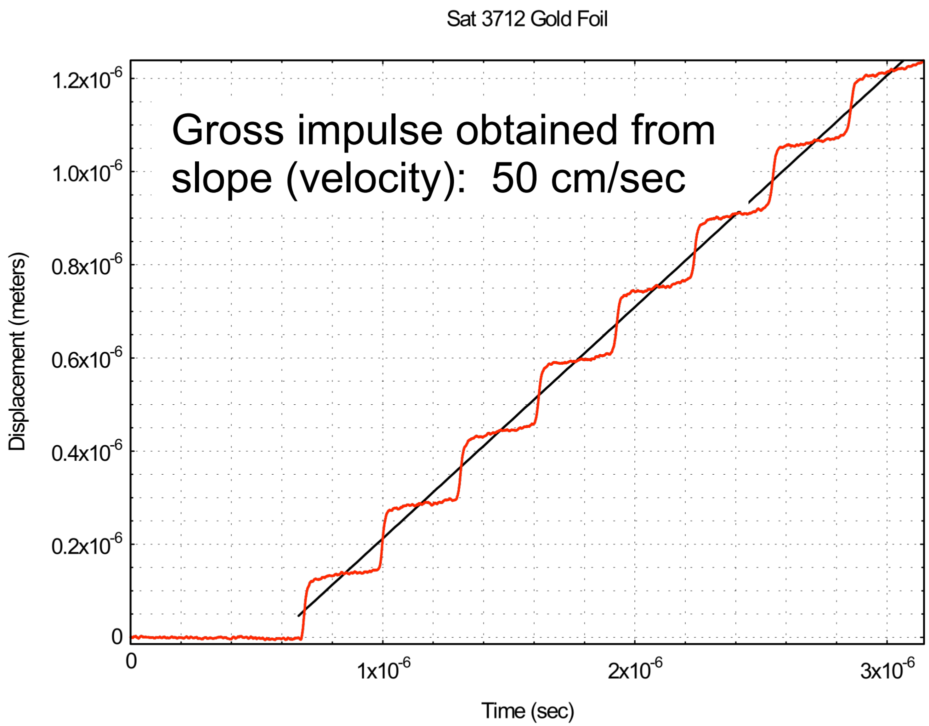
Impulse Measurement





Impulse response of 0.5 mm thick gold foil

Not amenable to time-frequency analysis

Delivered impulse: ~ 48 taps

(1 tap = dyne-sec/cm^2)

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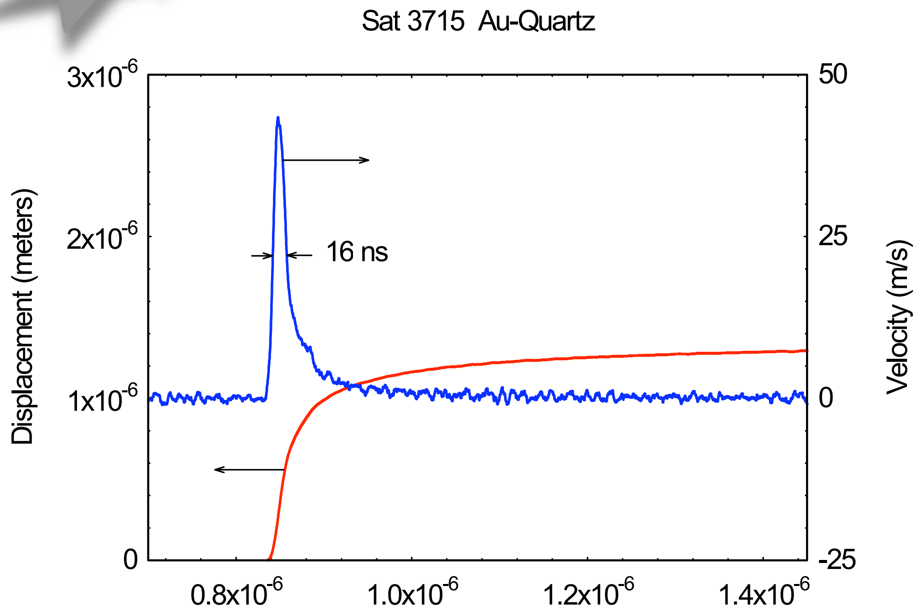
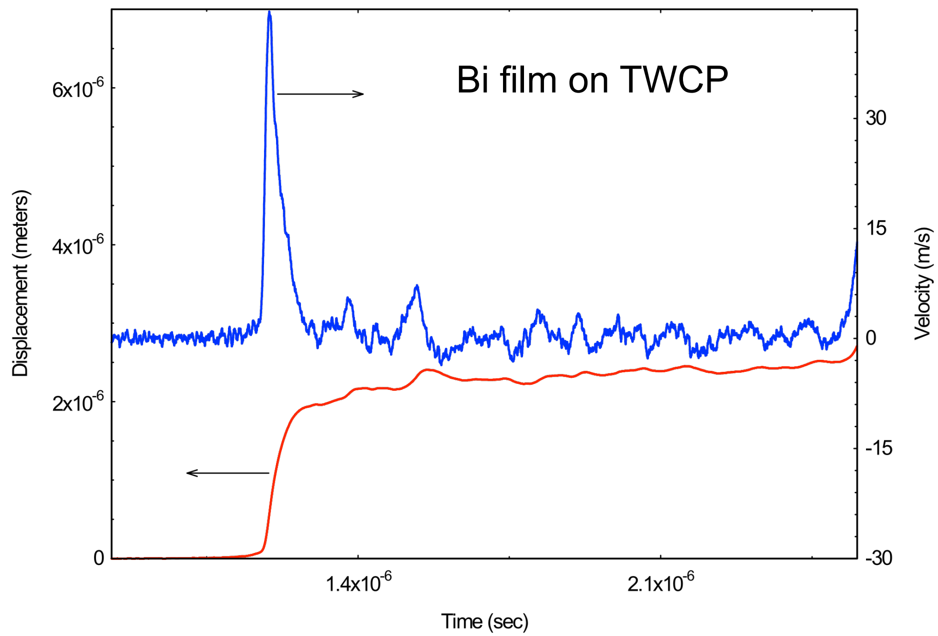
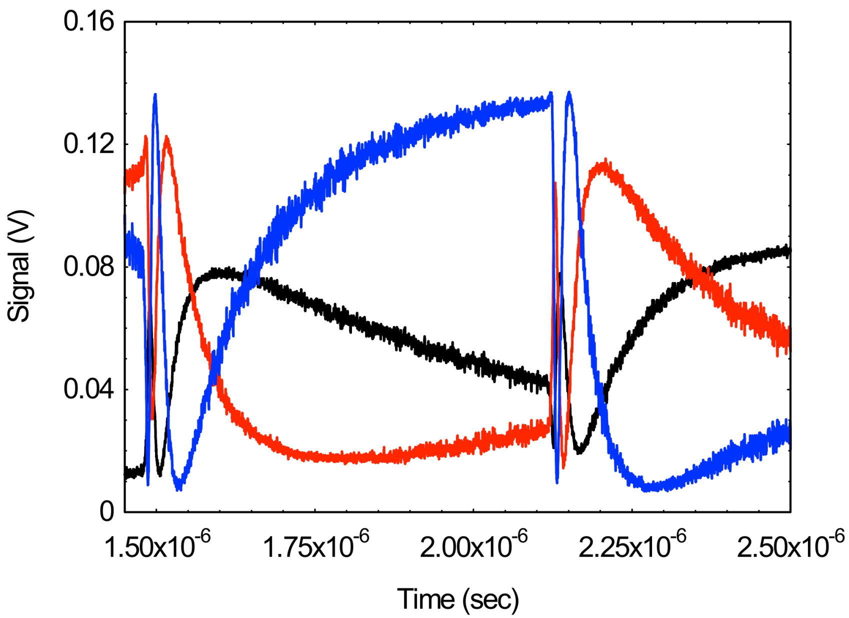
Impulse Measurement



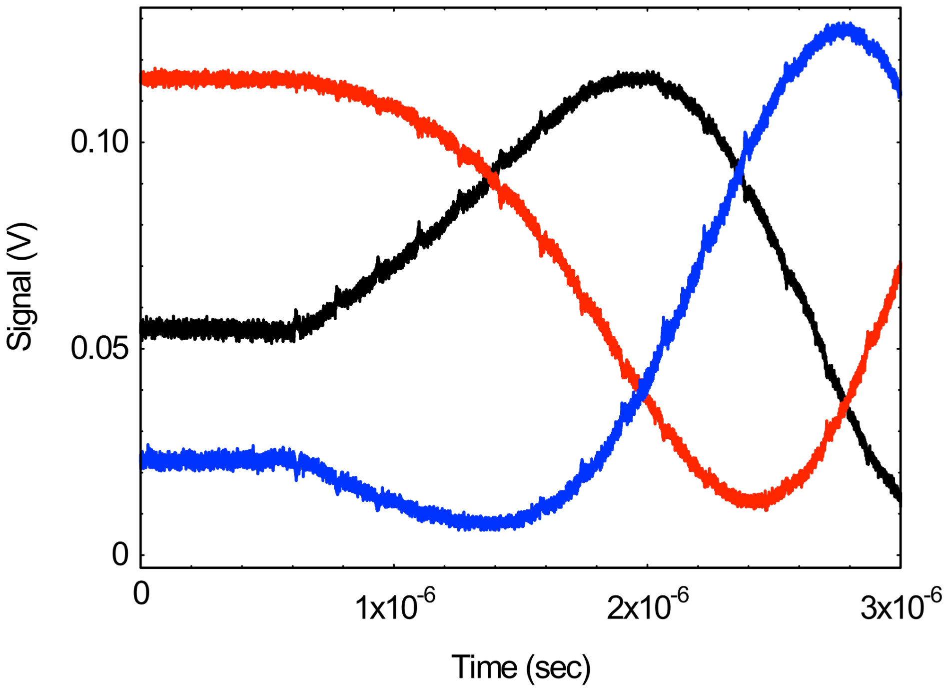


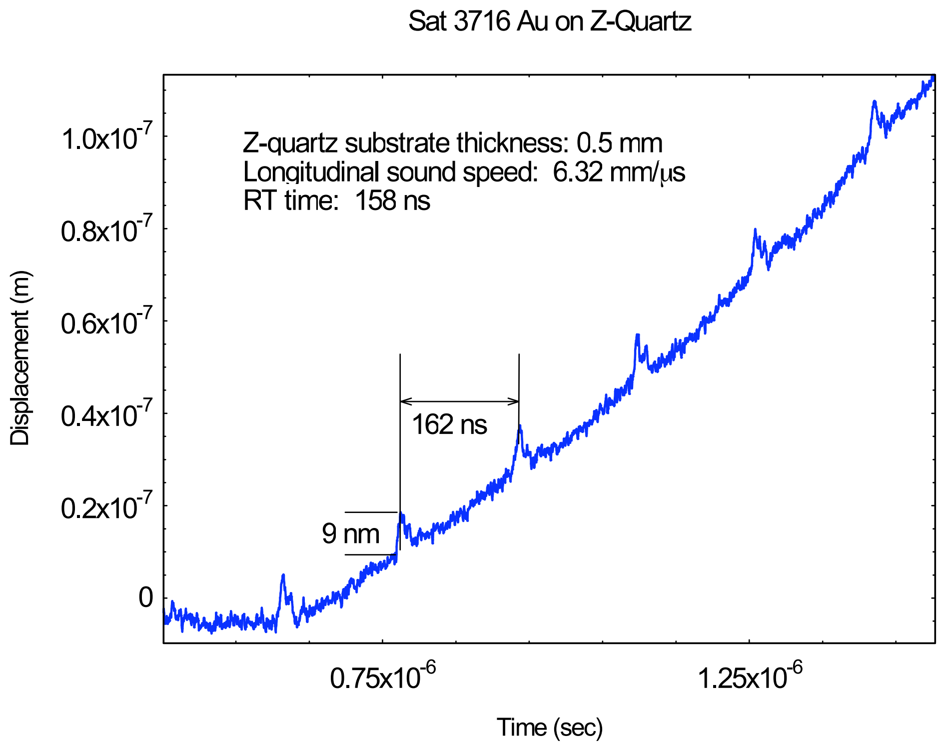


Gold film on Quartz crystal provides cleanest analysis for wave propagation in substrate and analysis of the vaporization/ melt dynamics

Bismuth coated TWCP impulse response. Note the 'noisier' response wrt to quartz, result of heterogeneity of substrate

Impulse Measurement





Low x-ray output on this shot – inadvertently allowed a demonstration of displacement sensitivity

9 nm ~ 0.016 fringe: Old adage is '.02 fringe resolution' !

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Summary

The quadrature PDV/PDI system has proven very useful for thermo-mechanical radiation response measurements

Direct analysis of displacement from signal phase allows measurement of motions where time-frequency analysis is not applicable and at velocities/histories where VISAR is readily useful.

THRIVE program makes data reduction really easy

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