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History of Velocimetry Technology

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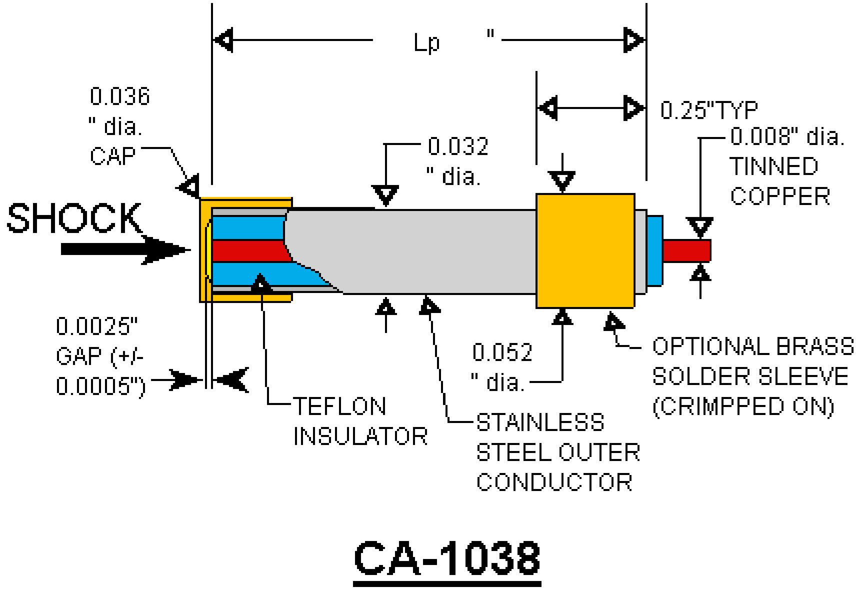
In the beginning there were . . .

Shorting Pins



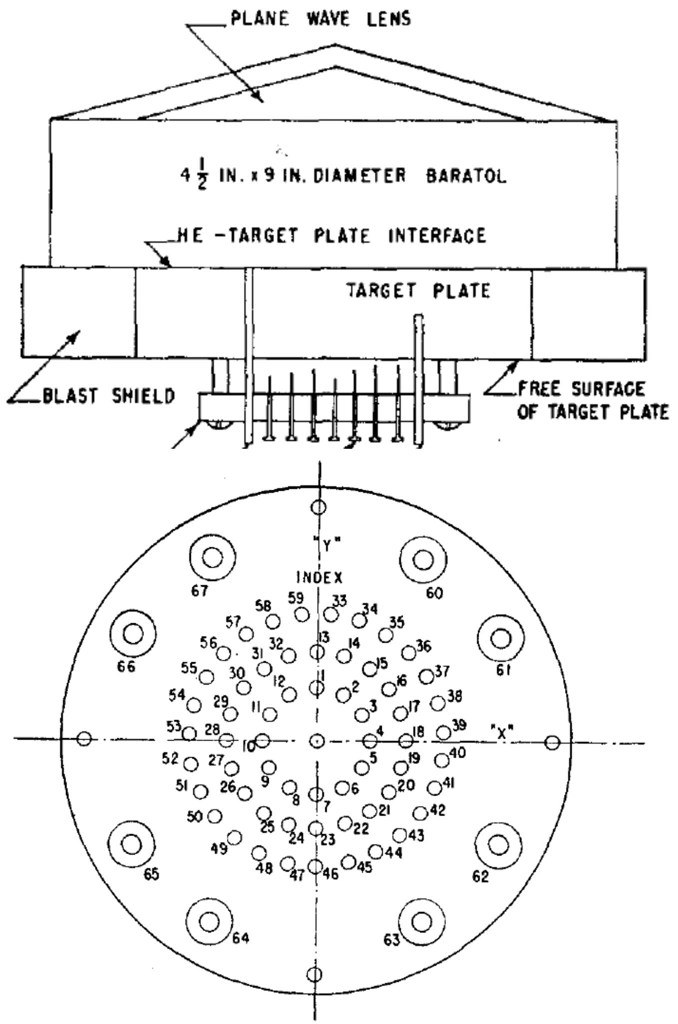
- Image from Dynasen, Inc. http://www.dynasen.com/html/shortingpinpage.html

Shock crushes metal casing to complete a contact between wires held at different voltages.

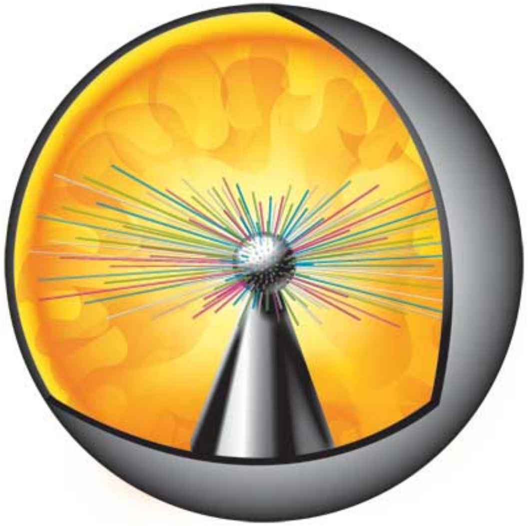
Series of pins would be staggered by known distances and velocity determined by measuring time differences between shorts.

Used 1940s to present, though largely supplanted by optical methods.

Uses of Shorting Pins



Planarity of explosive lenses.



Pin domes to measure implosion simultaneity.

Time-of-arrival devices (TOADs) do not directly measure velocity, but infer it from v = dx/dt.

Images from Dennison Bancroft, Eric L. Peterson, and Stanley Minshall, J. Appl. Phys. 27, 291 (1956) and https://www.llnl.gov/str/Sep07/Bosson.html contact *Steve Bosson (925) 424-3096 (stebo@llnl.gov)*

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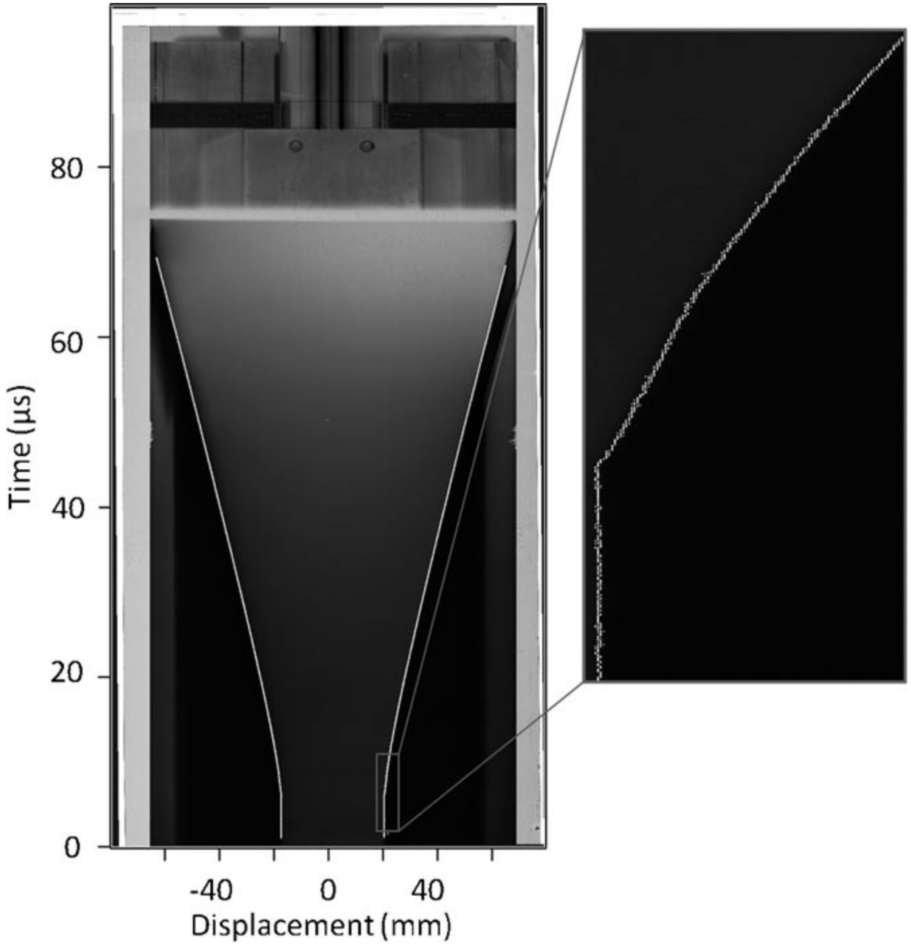
Optical Imaging



Cylinder expansion test imaged by streak camera

Image from C.M. Lindsay, G.C. Butler, C.G. Rumchik, B. Schulze, R. Gustafson, W.R. Maines; AFRL report **AFRL-RW-EG-TR-2012-050** http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA560937

Streak cameras image a 1D slit and streak the image of that slit across a recording device (CCD or film) to get time history.

Very popular method of determining Equations of State (EOS) of materials from 1950s to present.

Time resolution can be < 100 ps, but limited time window. (Window/resolution ~ 300)

High speed framing cameras may image a 2D surface, but typically only a handful of frames.

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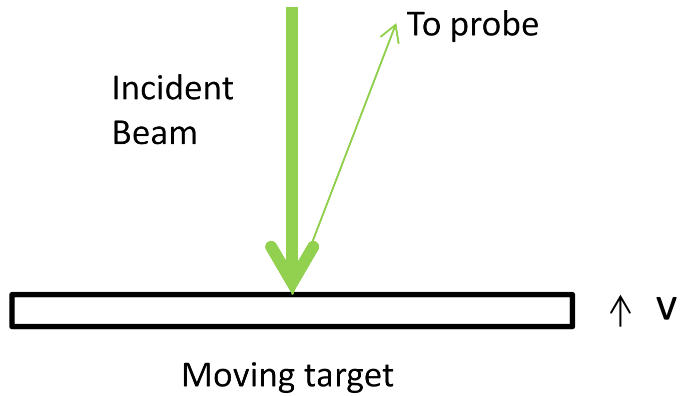
Interferometric Techniques

Moving target is illuminated with laser light and reflected light is Doppler-shifted in frequency.

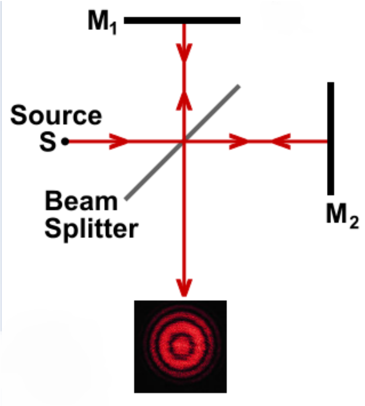


These techniques measure the phase shift of reflected light:
relative to a reference beam (*heterodyne*) or
a time-delayed copy of itself (*homodyne*).

The difference is important, so we'll discuss it further.

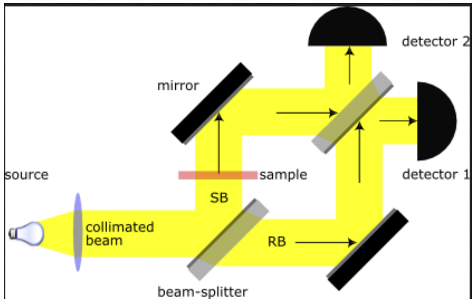
Homodyne vs. Heterodyne

Heterodyne interferometers produce fringes when the path length between beams changes, hence a ***position interferometer***.



A Michelson interferometer has a reference leg to a stationary mirror and another leg to a moving mirror. **It produces a fringe shift every time the moveable mirror moves half a wavelength.**

Homodyne interferometers produce fringes when there is difference in velocity (frequency) over a known delay time, hence a ***velocity interferometer***.



A Mach-Zender interferometer with a glass delay bar in one leg is a common implementation of a homodyne interferometer. **It produces a time-varying fringe shift only when the wavelength of light has changed over the time it takes to traverse the delay bar.**

Images from http://en.wikipedia.org/wiki/File:Michelson_interferometer_fringe_formation.svg and http://upload.wikimedia.org/wikipedia/commons/2/2d/Mach-zender-interferometer.png

Sandia Displacement Interferometer

First heterodyne interferometer for velocimetry described by Barker and Hollenbach at Sandia in 1965. Barker, L. M. and Hollenbach, R. E., Rev. Sci. Instr. 36,1617-1620 (1965).

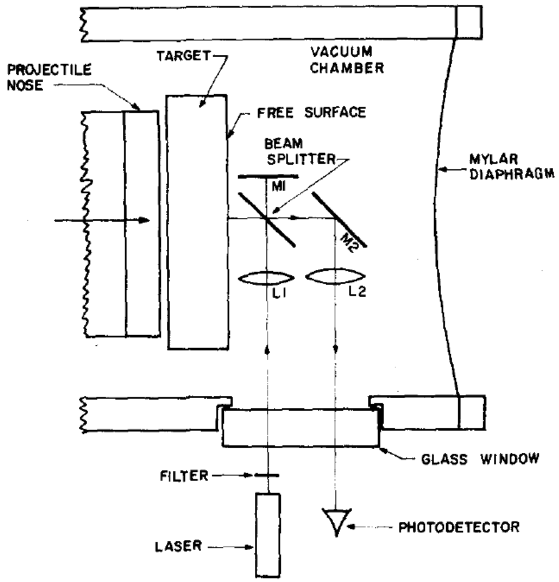


FIG. 1. Schematic of the interferometer configuration for measuring the free surface motion of the target specimen. M1 and M2 are mirrors. The lens L1 focuses the laser beam to a point on the free surface, and the lens L2 partially recollimates the light.

FIG. 3. Oscillogram showing the fringes produced by the initial free surface motion. The target was a 2.5 cm plate of annealed 1060 aluminum impacted at 30 m/sec by the same material.

- Limited to 100 m/s velocities because of oscilloscope bandwidth
- Interferometer is destroyed every shot
- Only useful for specular reflection (very sensitive to tilt of target)
- Gas lasers lase at several wavelengths with cavity modes separated by ~600 MHz (limits useful velocity range due to interference between modes)

VISAR

Velocity Interferometer System for Any Reflector (VISAR) developed in 1972 by Barker and Hollenbach. Improved to push-pull to increase signal-to-noise ratio and decrease sensitivity to incoherent light by Hemsing in 1979.

Hemsing. Rev. Sci. Instrum. 50, 73 (1979).

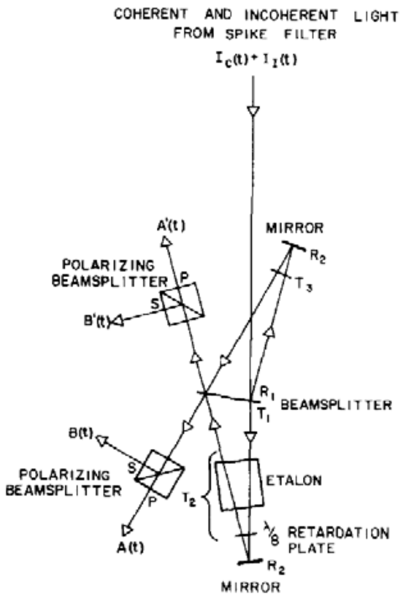


FIG. 3. Modified VISAR that uses previously wasted interferometer light to improve signals. A second polarizing beamsplitter has been added to obtain $A'(t)$ and $B'(t)$ and the intensity monitor has been deleted.

Homodyne interferometer with time resolution determined by etalon length (delay τ). Velocity averaged over τ.

Etalon length can be chosen to make beat frequency arbitrarily slow. Longer etalon means slower oscillations, but at the expense of time resolution.

If more than 2π radians of phase difference are accumulated in time τ, detector "misses a fringe" and creates an ambiguity in velocity.

Popular, wide applicability, robust, but expensive, complex, and not appropriate for resolving multiple velocities.

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Exotic Techniques

Fabry-Perot velocimetry developed ~1968 by Johnson and Burgess at LLNL. Homodyne technique that could resolve multiple velocities using a streak camera to record fringes. Expensive and difficult to use.

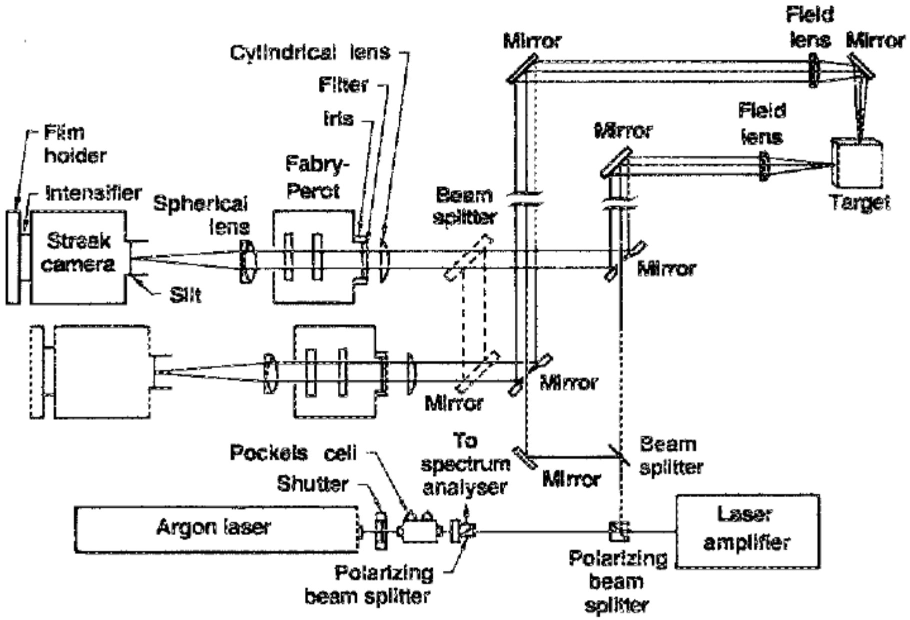


FIG. 6. Layout of a Fabry–Perot experimental setup typically used at LLNL.

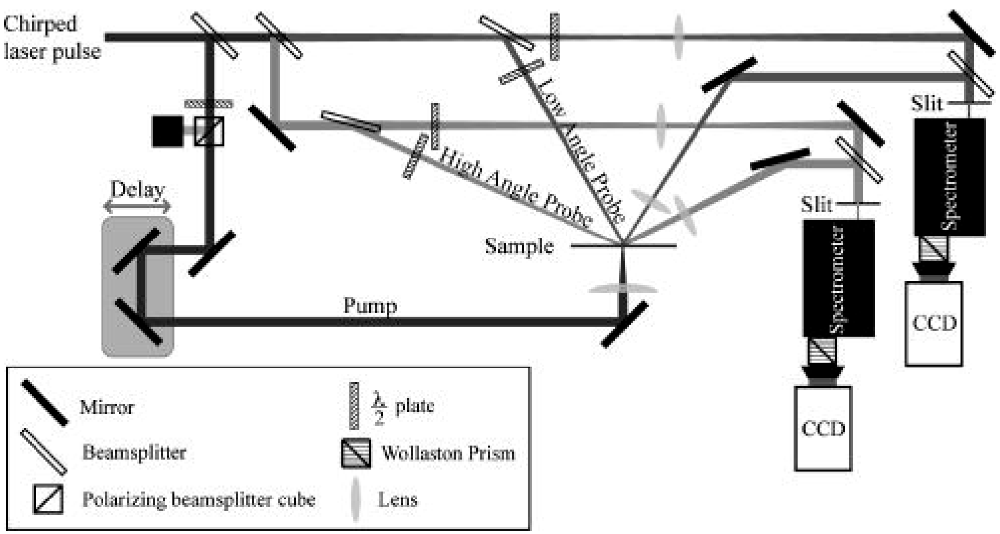
It's been said, "In terms of difficulty, VISAR is a 10, PDV is a 1, and Fabry-Perot is 100."

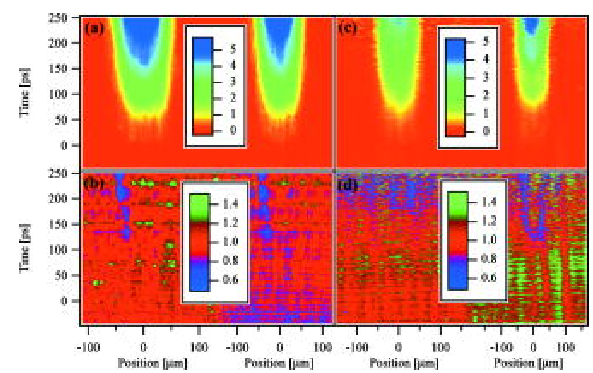
Images from Rev. Sci. Instrum. 59, 1 (1988); Velocimetry of fast surfaces using Fabry-Perot interferometry

Exotic Techniques

Ultrafast Dynamic Ellipsometry (UDE) developed by Bolme at LANL in 2007.

- Uses a chirped pulse from a femtosecond laser to encode time onto wavelength of probe pulse.
- Heterodyne technique that uses a spectrometer to record phase shift between a pulse sent to a sample and a reference pulse.
- ~10 ps time resolution, but record lengths only as long as pulse (~100s of ps)
- Measures shock velocity, particle velocity, and shocked index of refraction simultaneously.





Images from C. A. Bolme, S. D. McGrane, D. S. Moore, and D. J. Funk. J. Appl. Phys. **102**, 033513 (2007)

PDV

Photon Doppler Velocimetry (PDV) developed 2006 by Ted Strand at LLNL.

Rev. Sci. Instrum. 77, 083108 (2006);

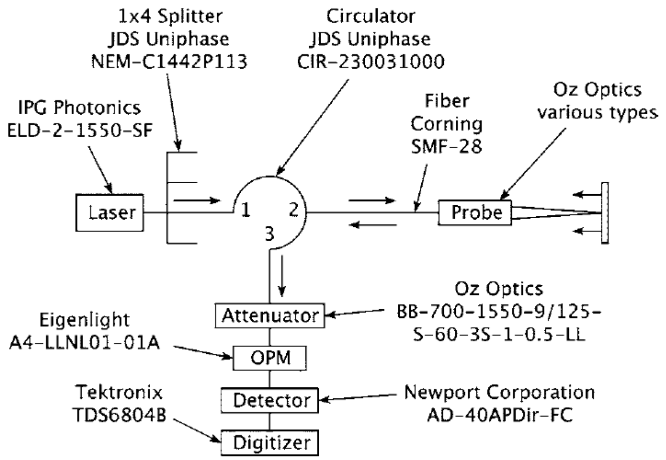


FIG. 2. The heterodyne velocimeter is assembled from commercially available parts.

Heterodyne technique that uses COTS parts from telecom industry.

Can resolve multiple velocities, robust, relatively inexpensive.

Fiber-coupled, so alignment of components is trivial.

PDV and VISAR signals

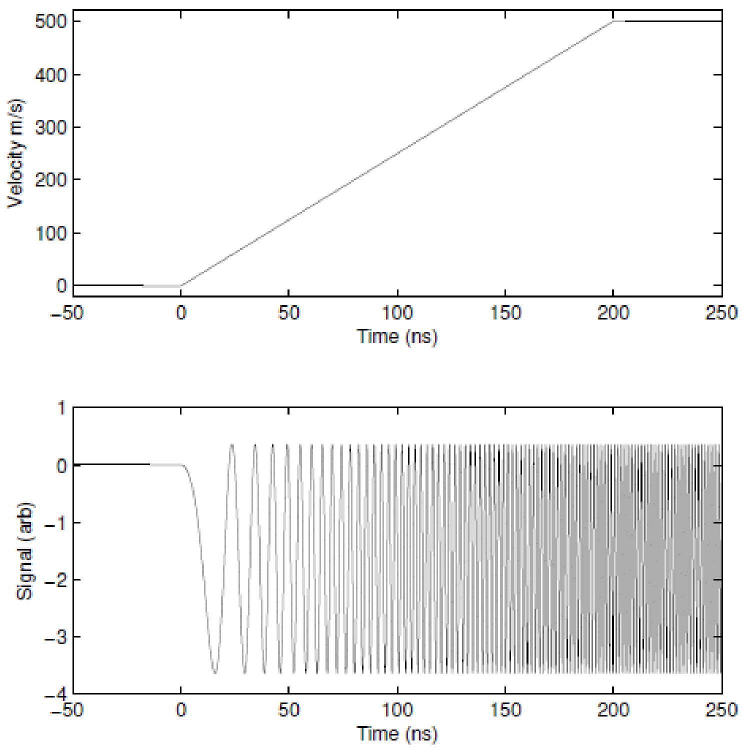


Figure 3. Example 2: (upper) input ramp velocity history; (lower) simulated PDV signal with AC coupling.

Signal caused by velocity ramp as measured by PDV.

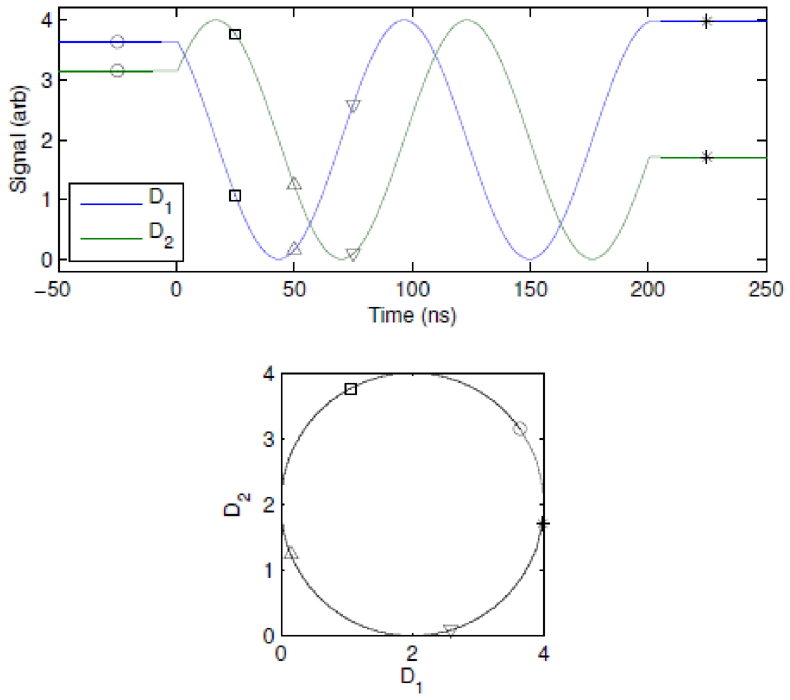


Figure 2. Example 1: (upper) input ramp velocity history; (middle) simulated VISAR signals; (bottom) VISAR ellipse.

Same ramp as measured by VISAR.

In PDV, frequency of oscillation is proportional to velocity. In VISAR, proportional to acceleration.

Images from Sandia Report SAND2011-0582. Dan Dolan. Velocimetry signal synthesis with fringen.

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Enabling Technologies

If the Sandia Displacement Interferometer (SDI) was reported in 1965, why didn't PDV come along until 2005?

Fiber lasers: He-Ne lasers used in SDI produced many frequencies separated by ~300 MHz, limiting useful velocity range of heterodyne interferometry. Fiber lasers have very narrow linewidths, long coherence lengths, and are very robust.

Optical Fiber: Low-loss fiber first made by Corning in 1970s.

Cooley-Tukey algorithm: Although invented by Gauss in 1805, the Fast Fourier Transform was popularized by a 1965 paper. SDI relied on counting fringes to determine displacement and numerical differentiation to get velocity. PDV uses FFT to extract velocity profiles.

Detectors and scopes: Photomultipliers and O-scopes used in 1965 had ~ 2 GHz of bandwidth. 20 GHz is common for both now.

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Why PDV?

- Simplicity: anyone can build one
- Robustness: only alignment is probe to target
- Commercially-available parts
- (Relatively) inexpensive
- Accurate: one fringe every half-wavelength of motion
- Can resolve multiple velocities thanks to FFT
- Algorithmic analysis: different users get same answers
- Versatility: useful for many kinds of targets and velocities