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Time-resolved velocimetry in dynamic compression research

VISAR versus PDV (HetV)

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National Nuclear Security Administration

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Overview

- Why do we measure velocity?

- Standard methods (widely used, scalable)
  - VISAR: 1960’s to present
  - PDV: 2003 to present
    - aka heterodyne velocimetry (HetV)

- Which diagnostic is better?
  - Velocity range
  - Uncertainty performance
  - Other factors

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Why do we measure velocity?

Why do we measure velocity?

Because we can!

Density and pressure are difficult...

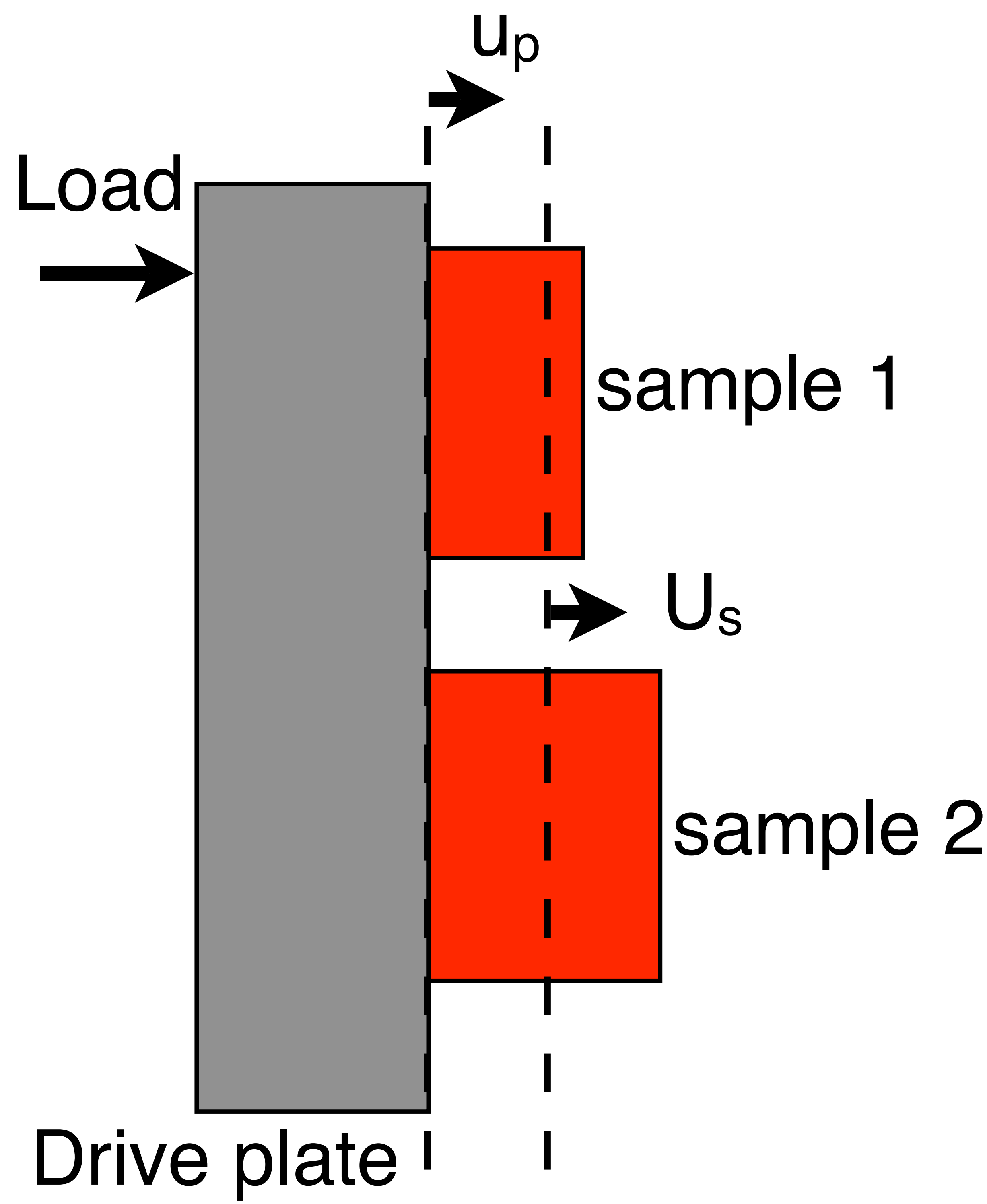
- ...but can be inferred from conservation laws

$$\frac{\rho}{\rho_0} = \frac{U_s}{U_s - u_p}$$ Jump conditions

$$P = \rho_0 U_s u_p$$

- Velocimetry also ties well with wave propagation codes

- Virtually all dynamic compression experiments involve velocimetry



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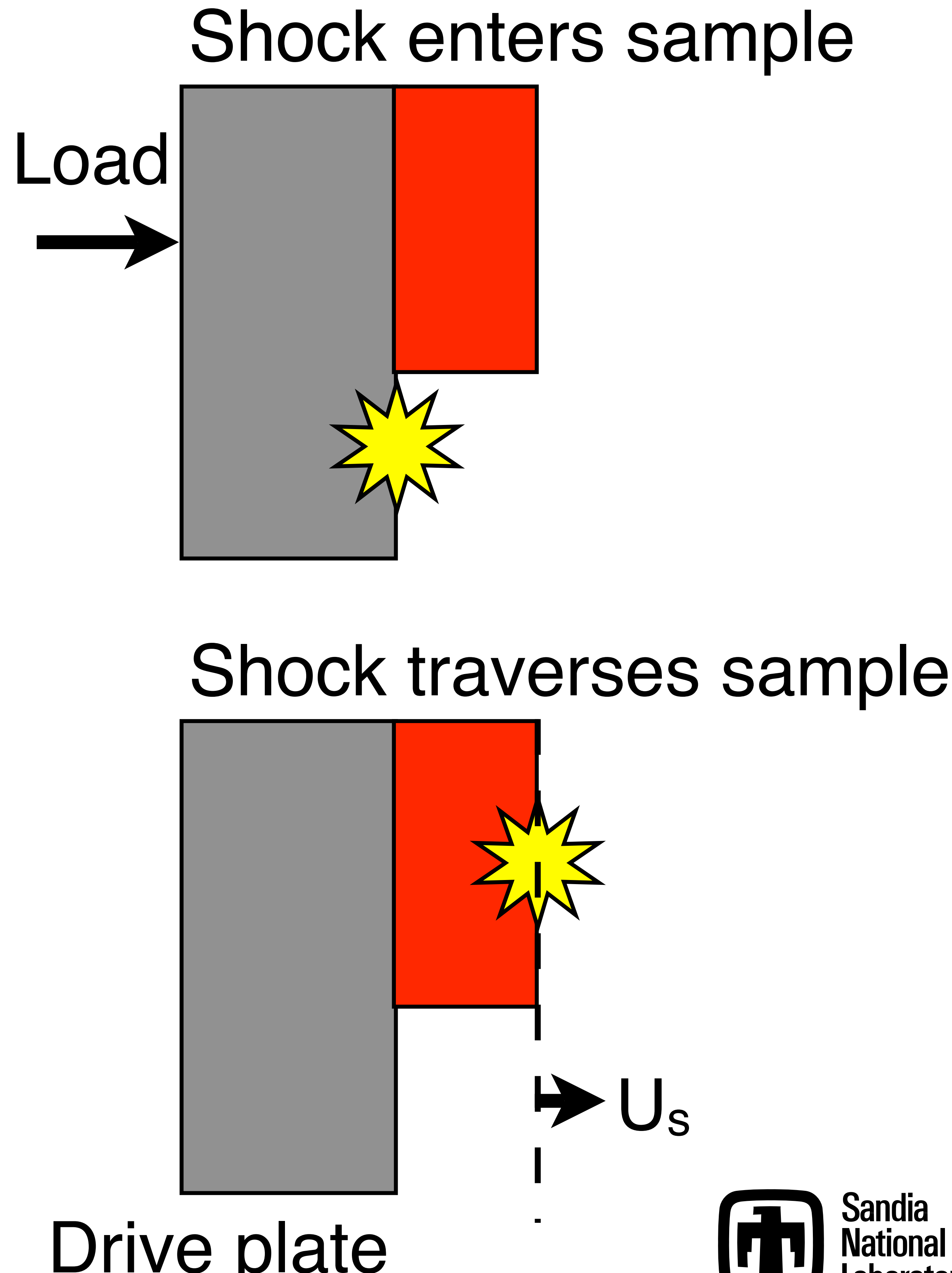
Basic velocimetry: transit time

- Electrical or optical shock breakout measurements

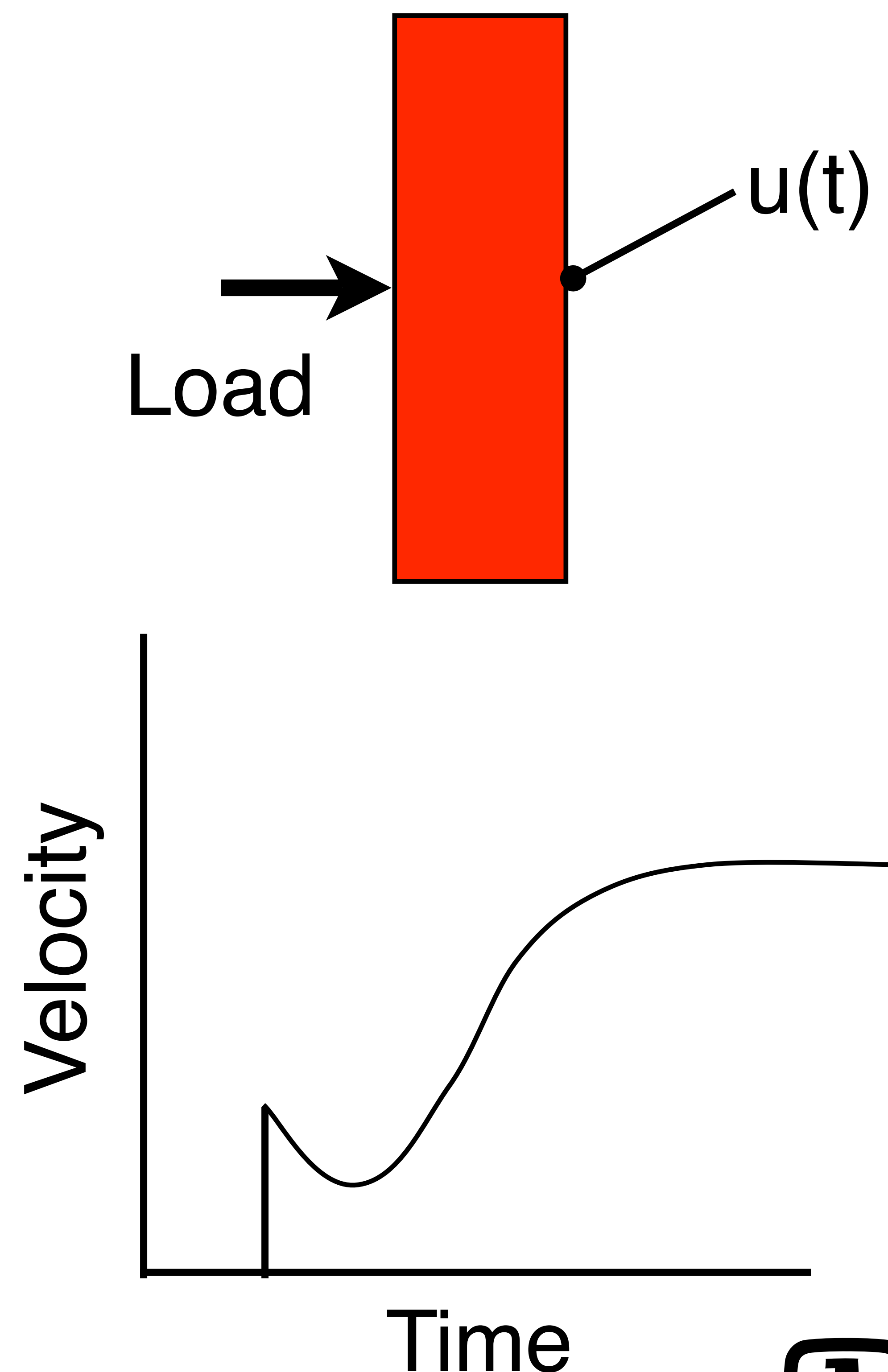
$$U_s = \frac{\Delta x}{\Delta t}$$

- Lots of data extracted from U_s
  - u_p inferred from impedance matching to standard drive plates
  - LANL shock tables



Time-resolved measurements

- Mechanical waves often contain a lot of structure
  - Inelastic compression
  - Phase transitions
  - Chemical reactions
- This structure is difficult, sometime impossible, to extract from transit time measurements
- Real-time velocity diagnostics are needed



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Optical velocimetry

- Optical methods are relatively simple to implement

- There are several different approaches
  - Optical emission
  - Reflected amplitude or direction
  - Most general techniques are based on optical phase

$$E(t) = A(t)\cos\phi(t) \qquad [\phi(t) \sim 2\pi f t]$$

Optical phase "wags" the electric field
Frequency is the rate of optical phase change
Wavelength is the reciprocal of frequency (scaled by c_0)

532 nm: 5.6×10^{15} Hz (1-2 fs period)

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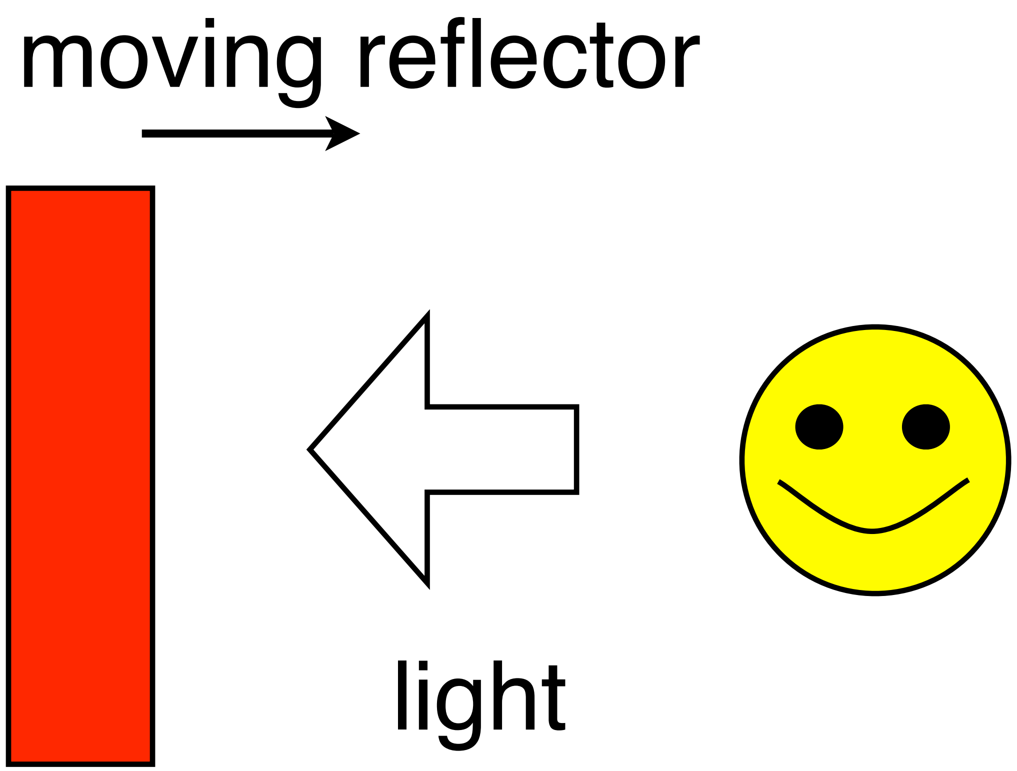
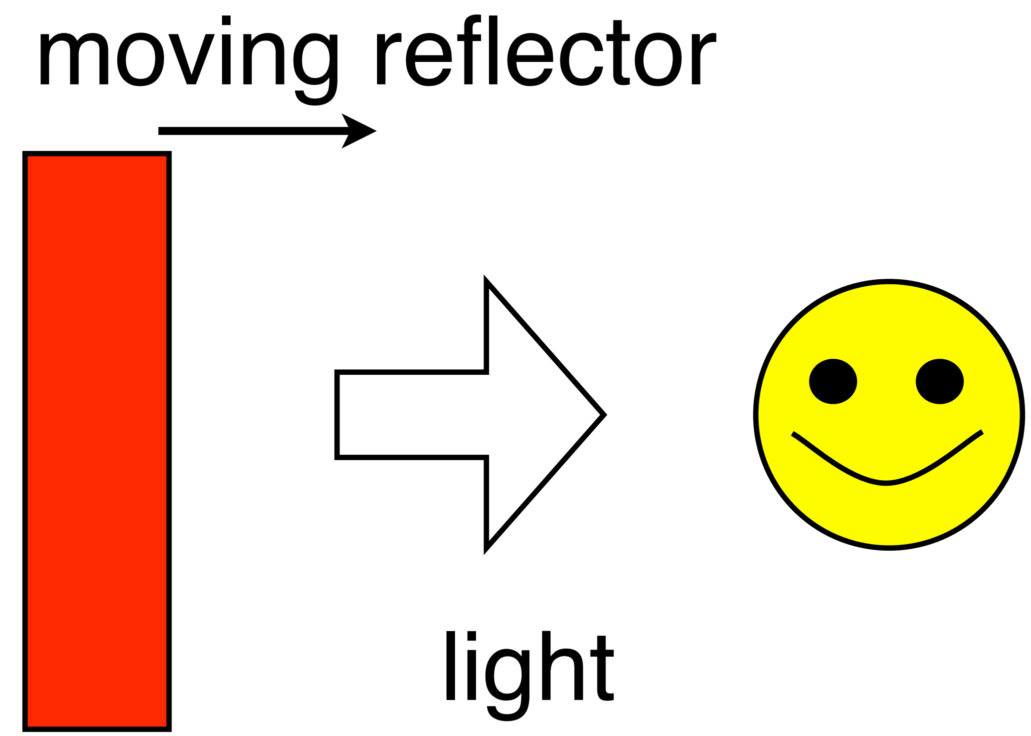
The Doppler effect





Observer sees: λ_0
Reflector sees: λ'

Reflected light: λ'
Observer sees: λ

$$\frac{\lambda}{\lambda_0} \approx 1 - \frac{2v}{c_0}$$

6-7 ppm change at 1 km/s
(0.004 nm at 532 nm)

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Interferometry

- Optical phase cannot be measured directly
  - Detectors sense average power over many optical cycles

- Wavelength changes are small for non-relativistic motion
  - Cannot by resolved by simple dispersion (i.e. prism)

- Some form of interferometry is required!
  - Two-beam systems:

$$I(t) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\underbrace{(\phi_1(t) - \phi_2(t))}_{\text{phase difference}}$$

(fields add)

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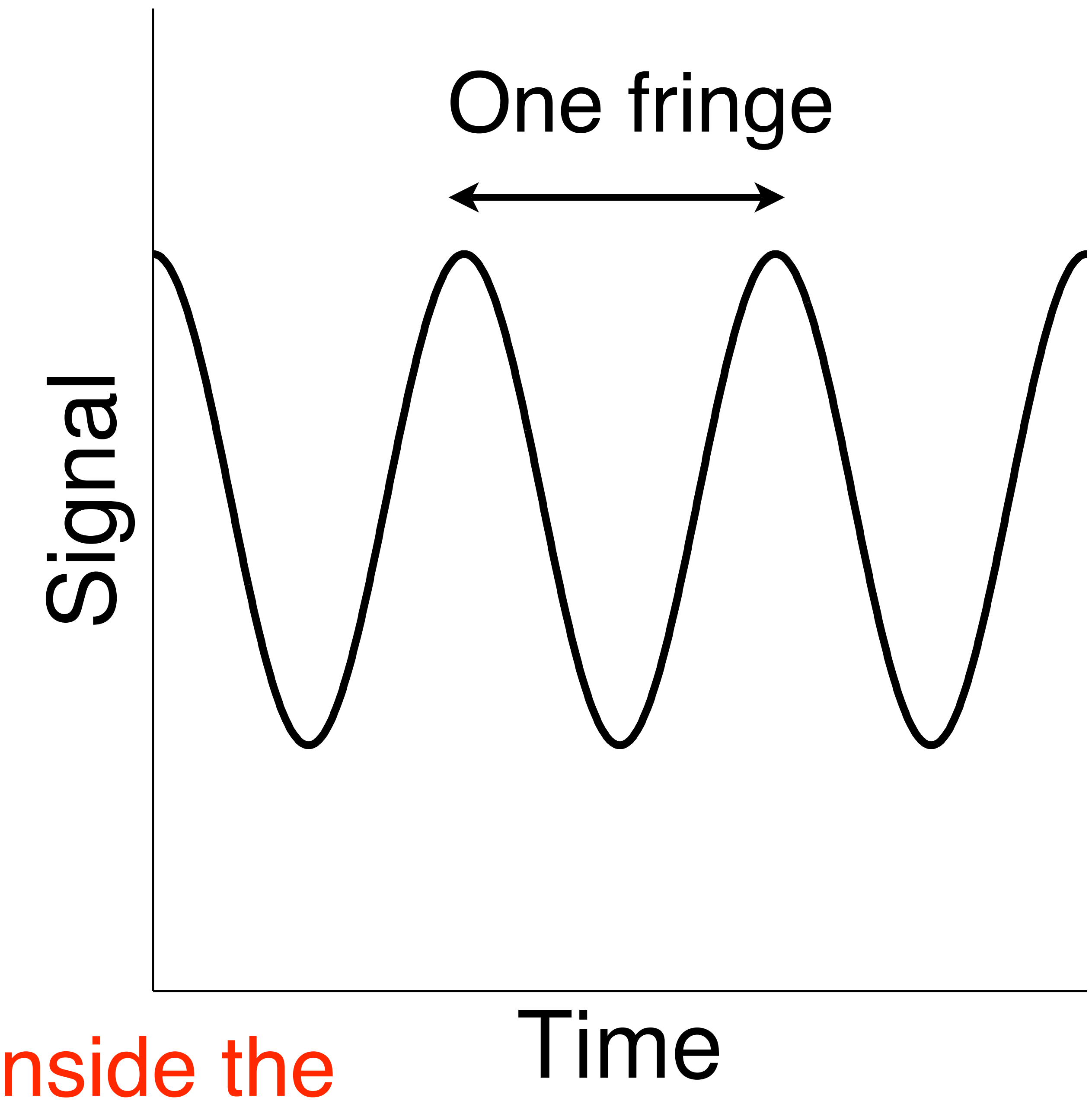
Some terminology

- Fringe shift (F)
  - Phase difference scaled by 2π
  - Number of cycles
- Beat/fringe frequency (f_B)
  - Rate of **signal** cycles
  - Not the same as the optical frequency



We measures what goes on inside the cosine function of the **signal**, not the electric field

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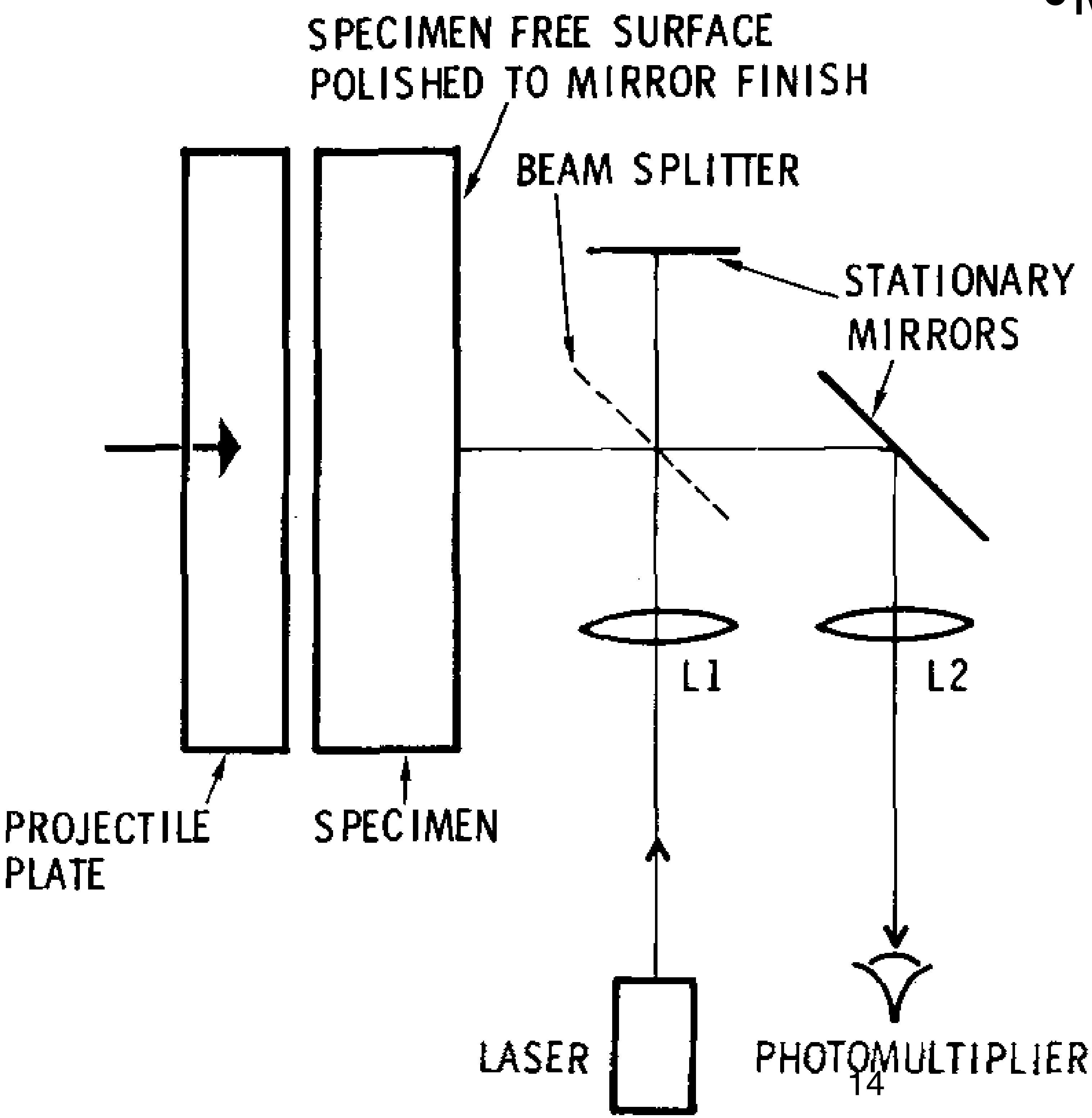
Method I: VISAR

Making due with limited bandwidth

Some history (1960-1970)

- Sandia displacement interferometer



- Michelson configuration
  - 1 fringe = 1/2 wavelength motion
  - L.M. Barker, Experimental Mechanics **12**, 209 (1972).

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There were problems...

- Mirror finish required for usable fringes
  - Surface finish often changed during shock breakout

- Limited velocity range
  - Beat frequency scales with velocity
  - At 632.8 nm, 1 km/s velocity creates a 3.16 GHz signal!
  - No detector/digitizer could follow such frequencies in the 1970's

$$\frac{dF}{dt} = f_B = \frac{2u}{\lambda_0}$$

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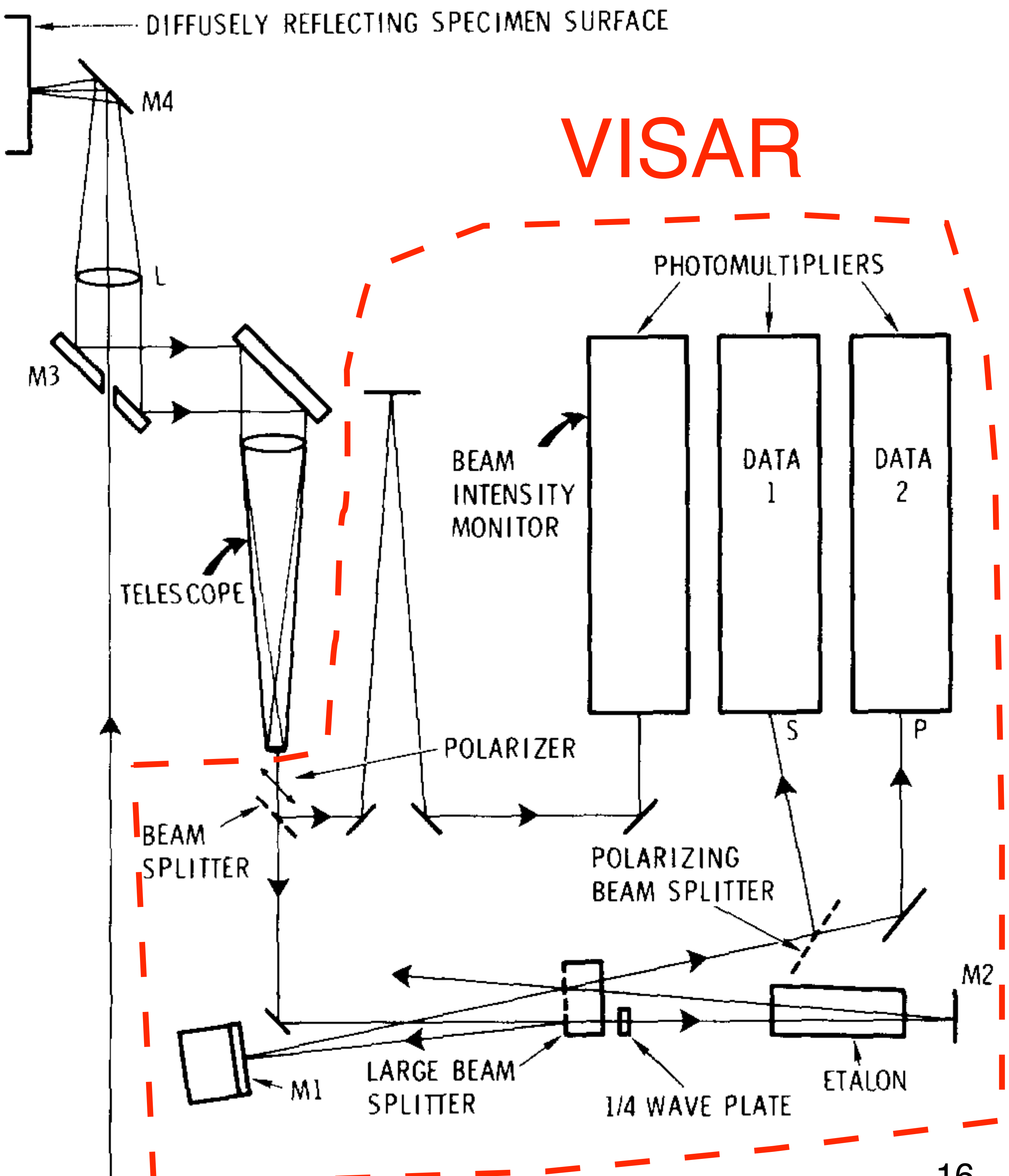
Thus VISAR was born



- Doppler shifted light mixed with a time shifted version of itself
  - Avoids large steady-state frequencies
- Etalon allows diffuse reflectors (“any reflector”)
- Barker and Hollenbach, J. Appl. Phys. **43**, 4669 (1972).

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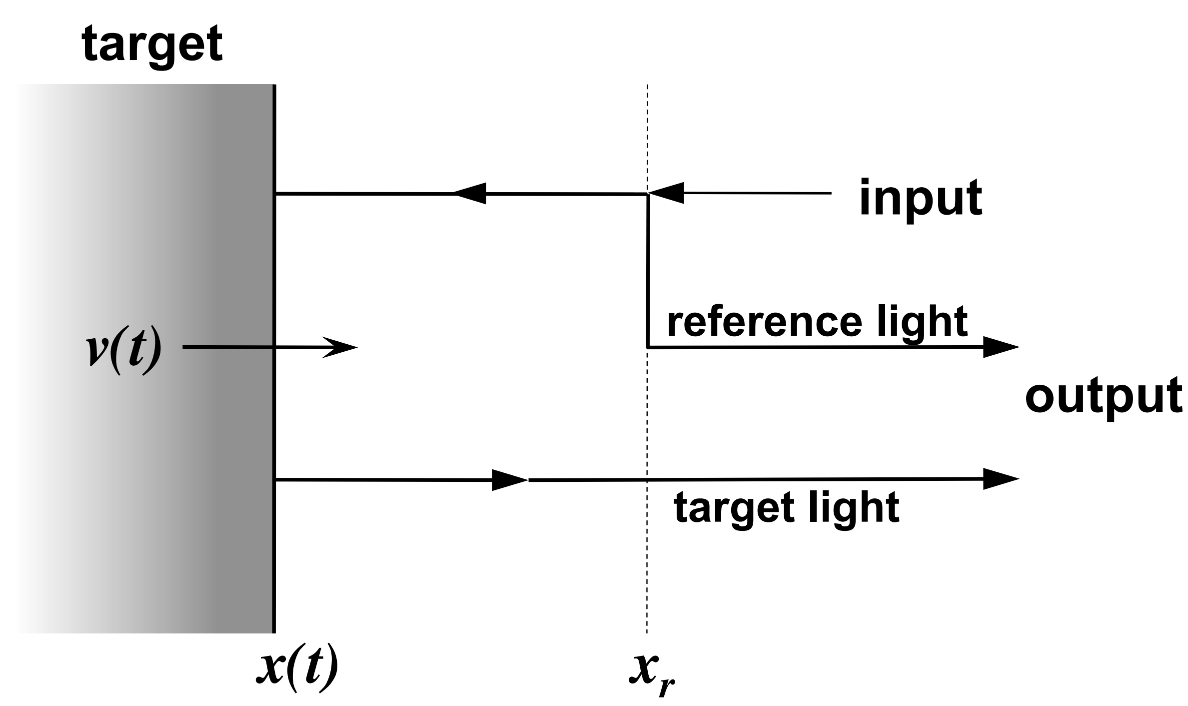
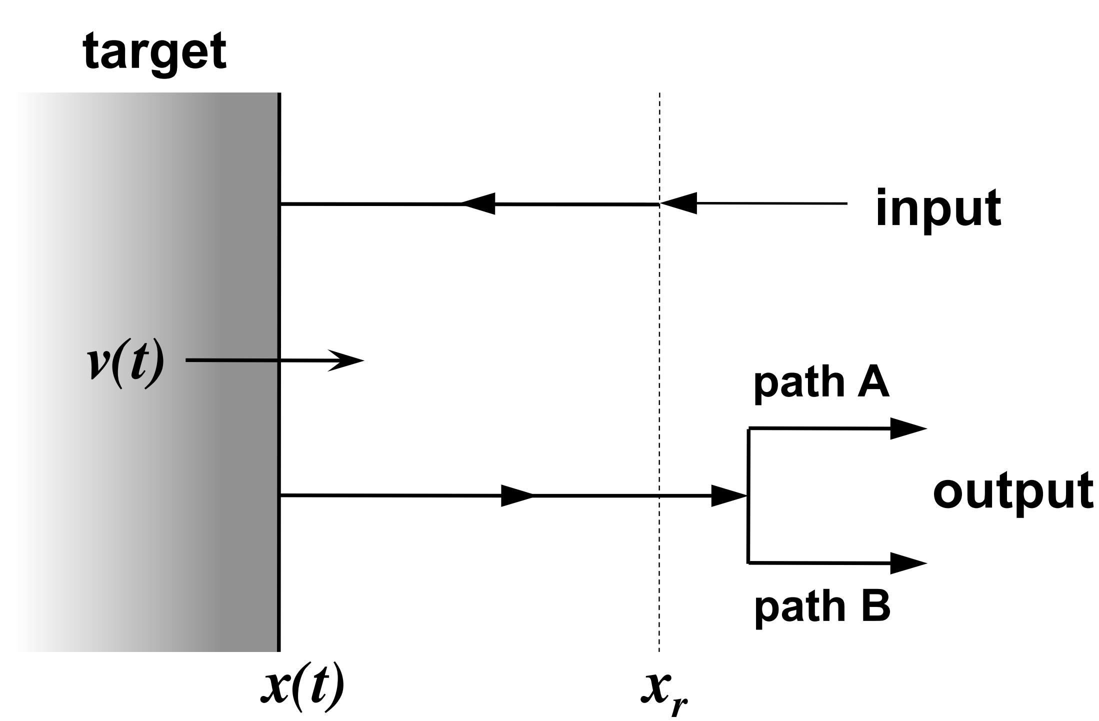
The critical difference

- "Displacement" approach
  - One output path contains target (Doppler)
  - Other output path does NOT contain the target
  - Mixes two different frequencies



- "Velocity" approach
  - Both output paths contain the target (Doppler)
  - Mixes two copies of a single frequency*



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*The VISAR approximation

- For constant velocity, both legs of a VISAR contain the same optical frequency
- **IF** velocity changes slowly compared to the delay time:
  - Fringe shift scales with velocity when (approximation)
- Exact behavior is more complex
  - Differential displacement
  - A great deal of pain involved...
- Sensitivity defined by wavelength and delay time
  - Fringe constant
  - Velocity Per Fringe (VPF)

$$F = \underbrace{\frac{2\tau}{\lambda_0}}_{\text{VPF}} u$$

$$\tau \approx 0.1\text{–}10 \text{ ns}$$

Smaller is hard to characterize, larger is hard to build

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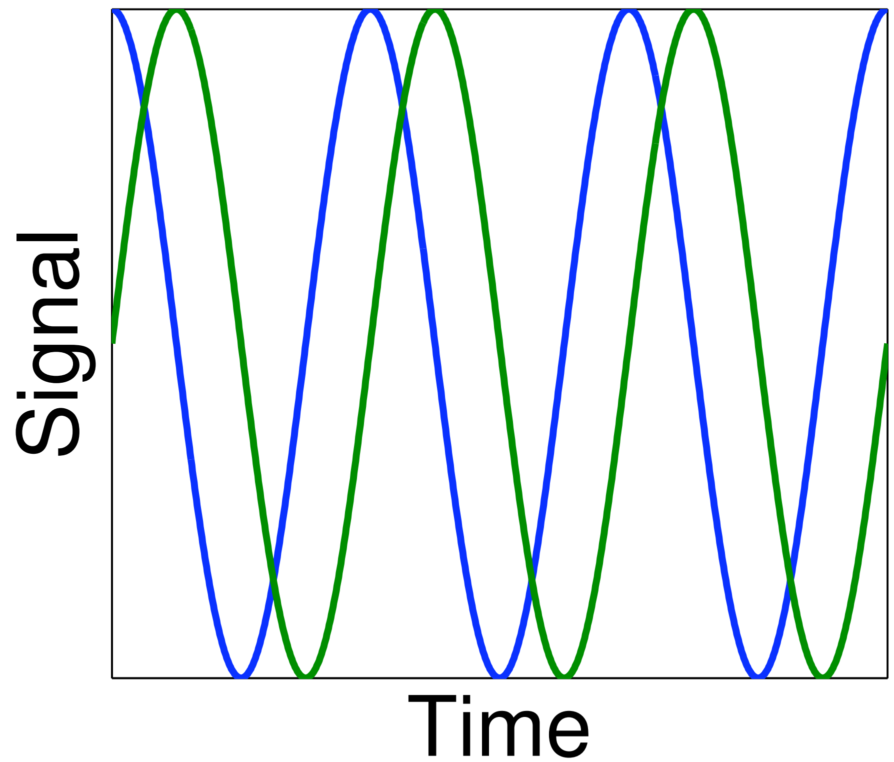
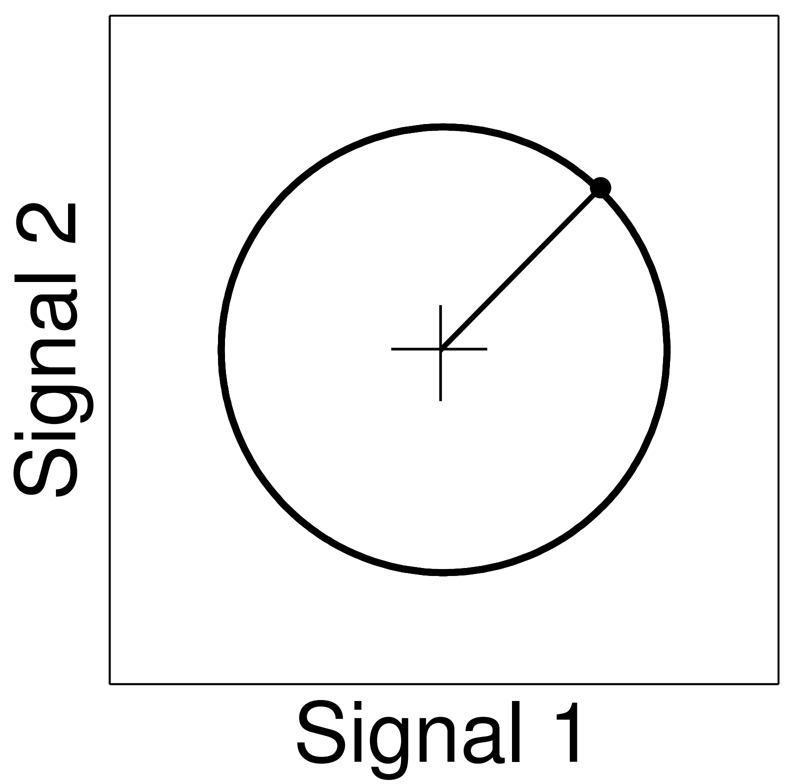
The need for quadrature



- Inverting a sinusoid is not always easy
  - Arcsine and arccosine defined over 180 degrees
  - Steep sections are sensitive
  - Peaks/troughs are insensitive



- Measuring 2+ quadrature signals provides:
  - A robust inversion
  - Reduces the effect of amplitude variations
  - Arctangent defined over 360 degrees

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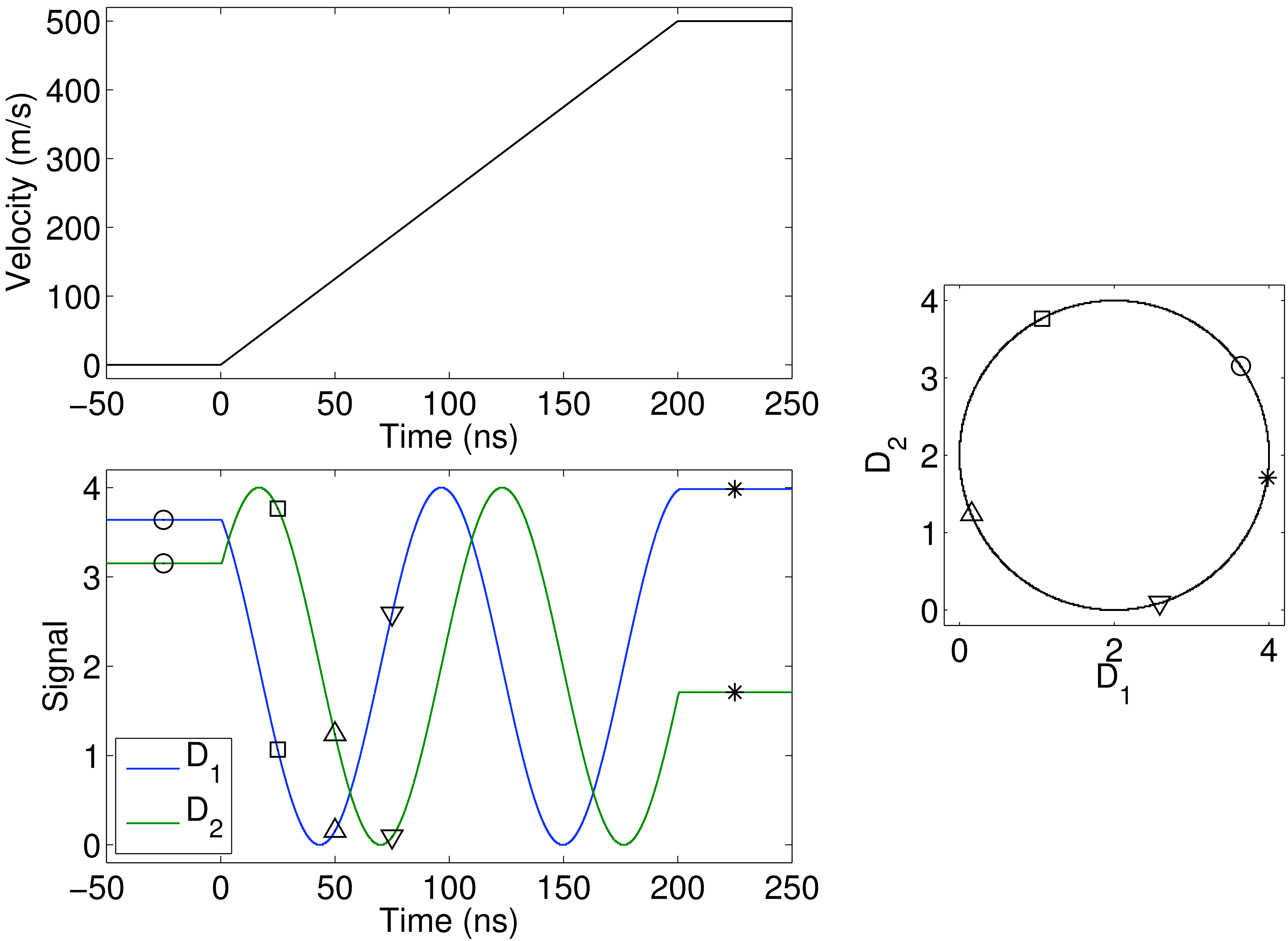
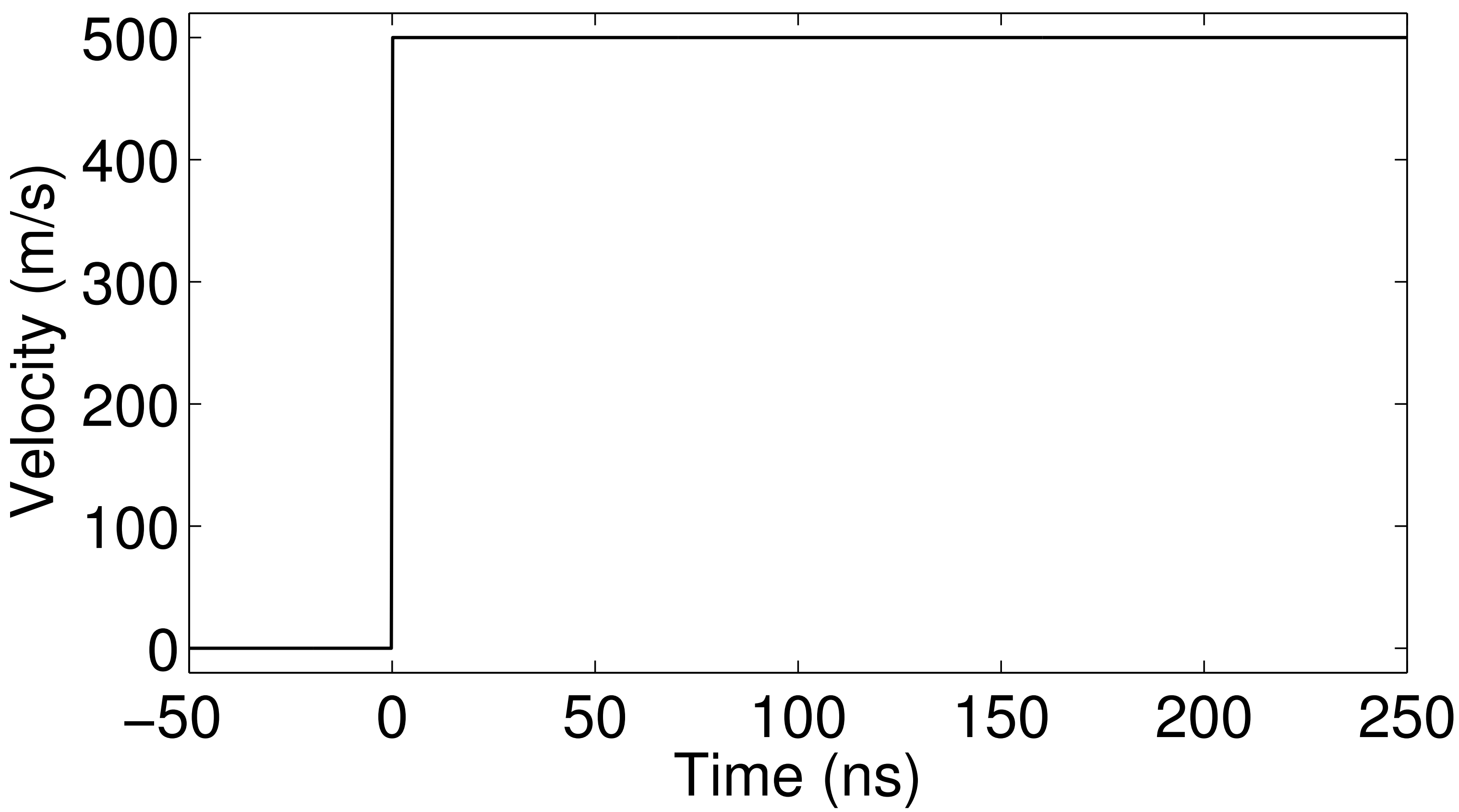
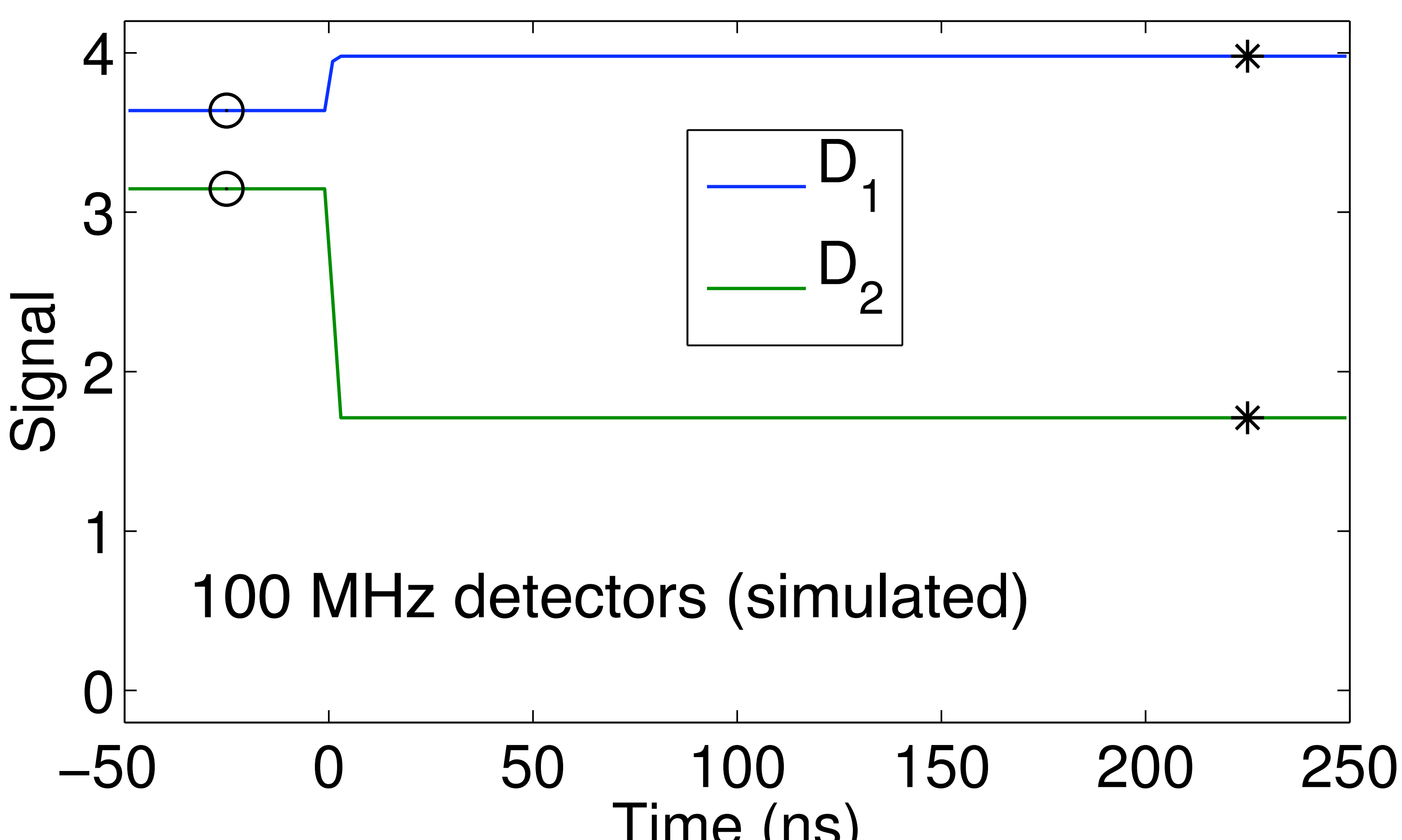
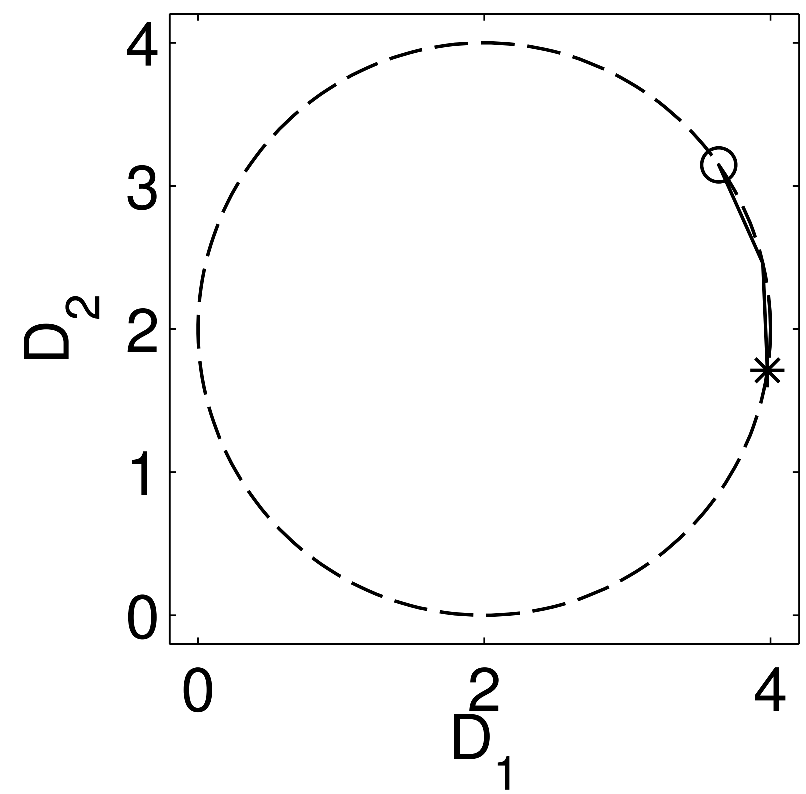
Ramp example (1 ns delay)



Shock example (1 ns delay)







Why does the motion look backwards?

Reality sets in

- Quadrature only tracks fringe shift within an integer offset
  - Detectors that cannot keep up with optical signal may "jump a fringe"
  - Multiple VPFs are generally used to resolve this ambiguity

$$\cos(\Phi) = \cos(\Phi + 2\pi) = \cdots$$

$$\begin{aligned} u &= K_1(F_1 + N_1) \\ &= K_2(F_2 + N_2) \end{aligned}$$

- VISAR is designed to measure fringe shift from a **single** Doppler shift
  - Multiple velocities cause confusing interference
  - VISAR ellipse will collapse to its center

- Ellipse position and size changes with light level!

VISAR evolution

- Refined quadrature measurement
  - Four signal phases (0, 90, 180, and 270 degrees)
  - Explicitly remove coherent/incoherent light variation
  - Hemsing, Rev. Sci. Instrum. **50**, 73 (1979).

- Fiber coupling
  - VISAR was originally an open-beam diagnostic

- Faster detectors
  - Optical streak-cameras
  - Improved photodiodes/photodetectors
  - Faster digitizers

- Not much fundamental change over the past two decades

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Method II: PDV

Using bandwidth when you've got it

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What's the problem with VISAR?

- An intrinsic time scale (interferometer delay)
  - Short delay: poor velocity resolution
  - Long delay: poor time resolution and tricky analysis

- Multiple velocities confuse the fringe shift calculation
  - Dynamic contrast loss

- Detector artifacts (rise time, ringing) become a problem
  - Sample time is now usually much shorter than the interferometer delay

- System care is labor intensive
  - Interferometer alignment
  - High power lasers
  - VISAR alternatives (Fabry-Perot) even more work

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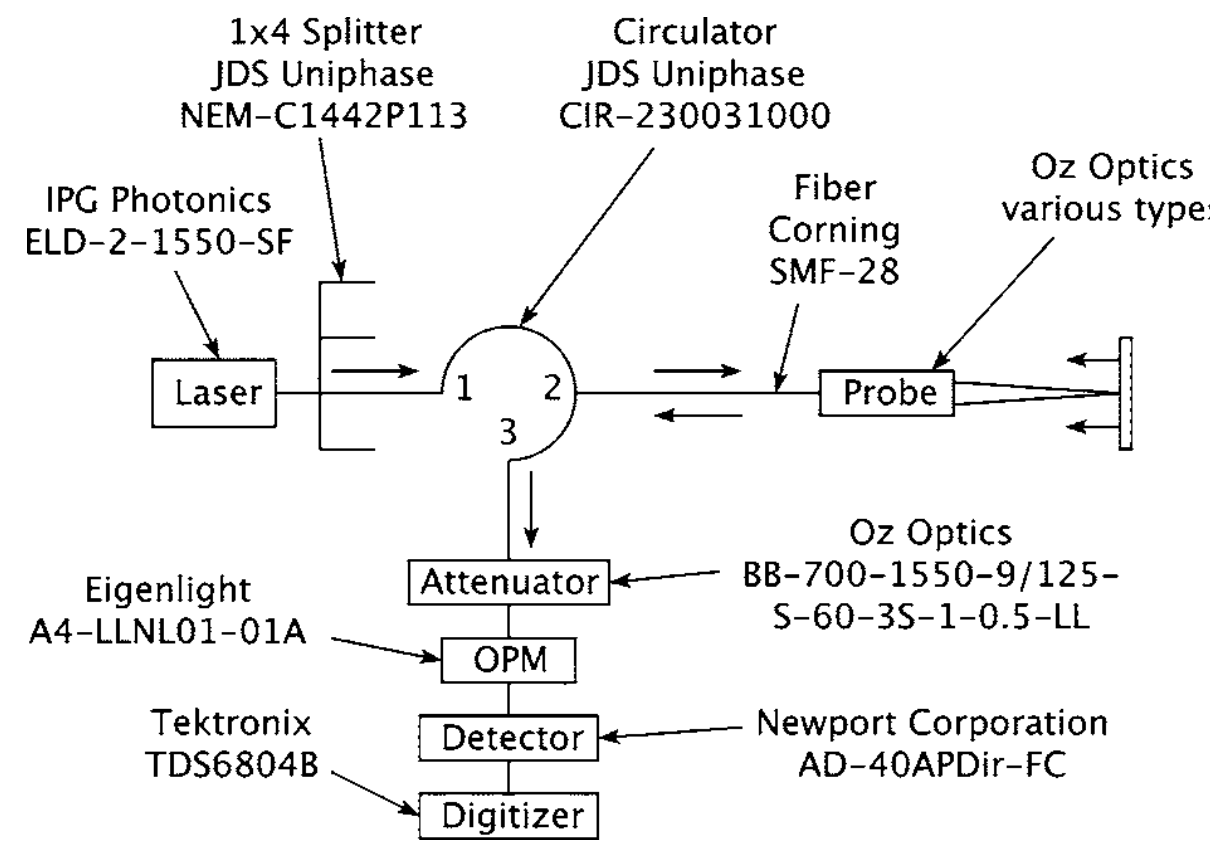
PDV born at LLNL (2002-2003)

- Utilizes advances from the telecommunications industry (1550 nm)
  - Compact fiber lasers
    - 9 um core size
    - Narrow line width
  - Three-port circulator (magic!)
    - Port 1 input goes to port 2
    - Port 2 input goes to port 3
  - High speed detectors/ digitizers



Strand et al, Rev. Sci. Instrum. **77**, 83108 (2006).

Generation 0: reference light comes from the probe's back reflection

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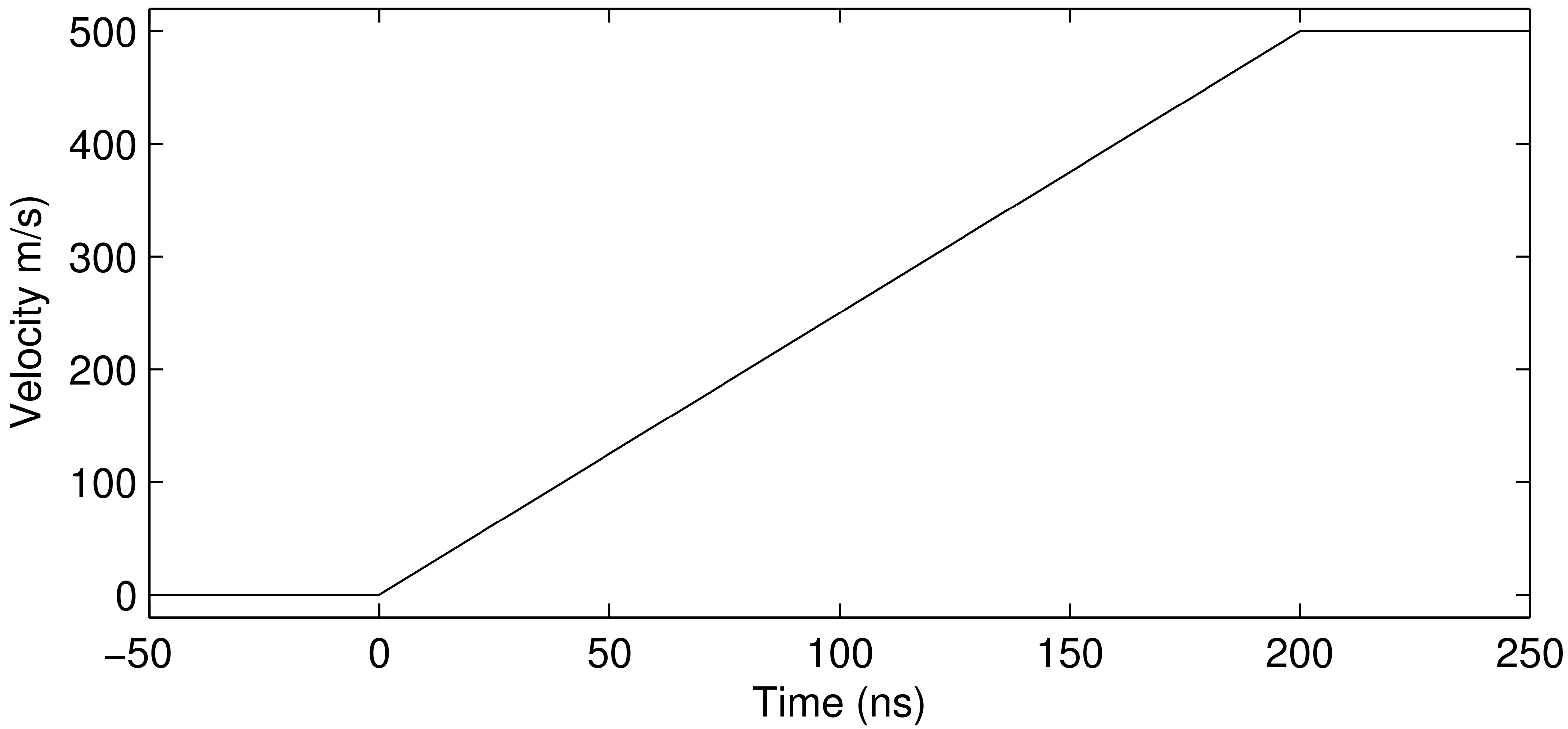
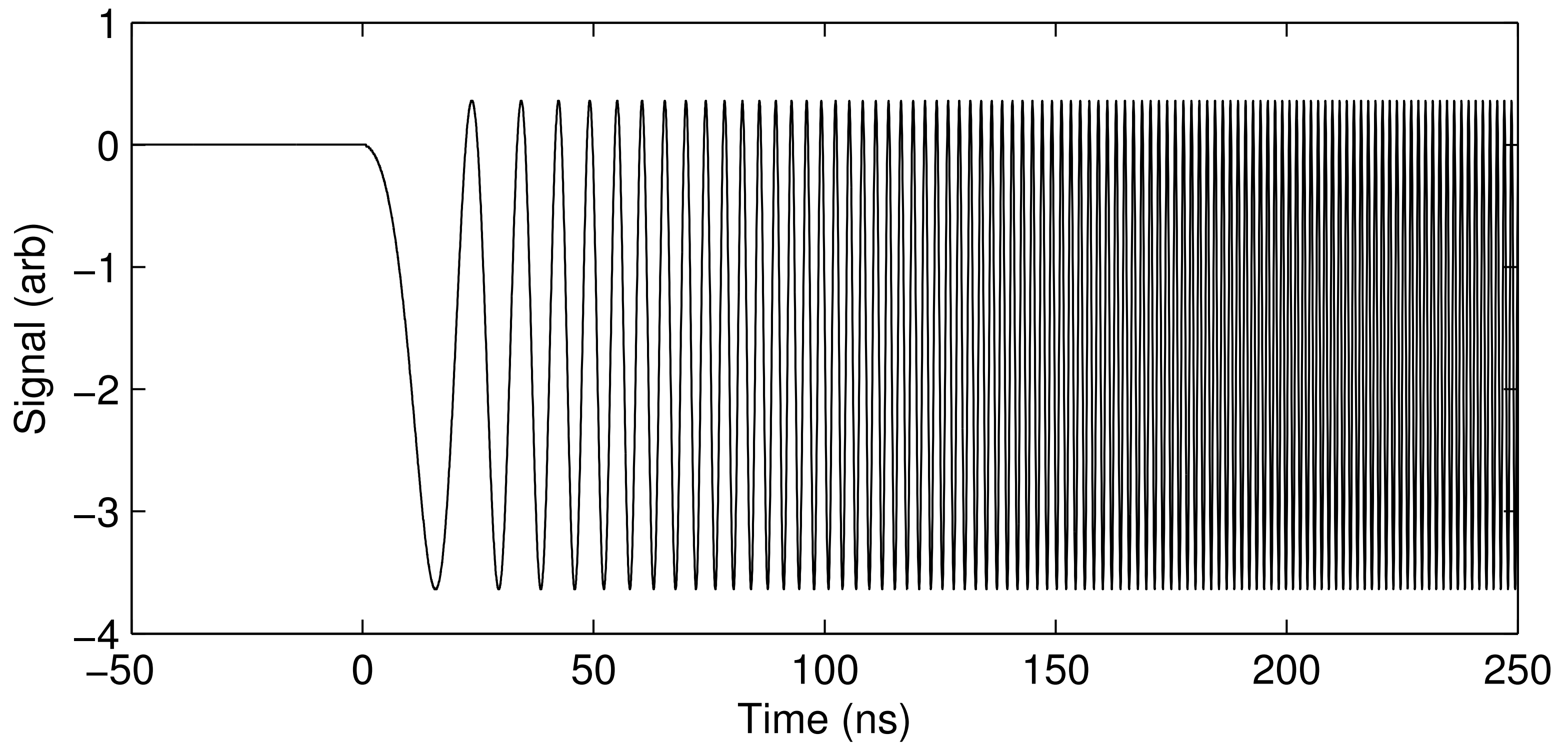
Ramp example





- Michelson interferometer
  - 775 nm motion= 1 fringe
- Signal frequency increases with velocity

Displacement interferometer lives again (in fiber)!

$$\frac{dF}{dt} = f_B = \frac{2u}{\lambda_0}$$

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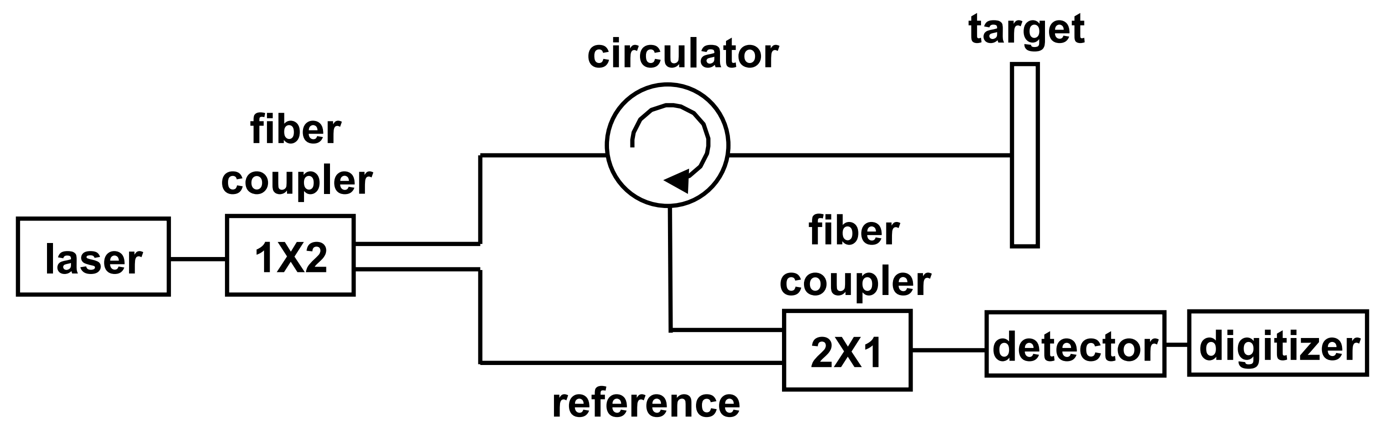
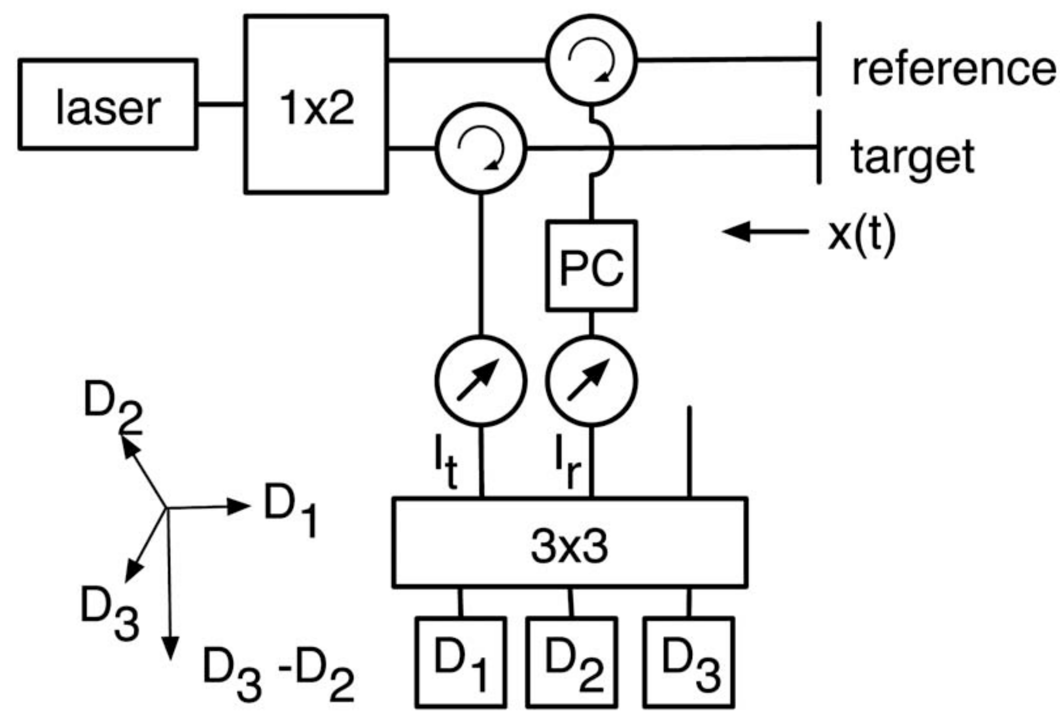
Initial modifications

- Generation 1
  - Reference path separate from the probe (angle polished)
  - Increases target/reference light control
- Quadrature PDV (TDV,PDI)
  - 3x3 coupler creates 120 degree phase shifts
  - Analysis is similar to VISAR, but result is displacement
  - Better than conventional PDV below ~500 m/s
  - Direction information



“Conventional” PDV [SNL,LANL]



Quadrature PDV [SNL]

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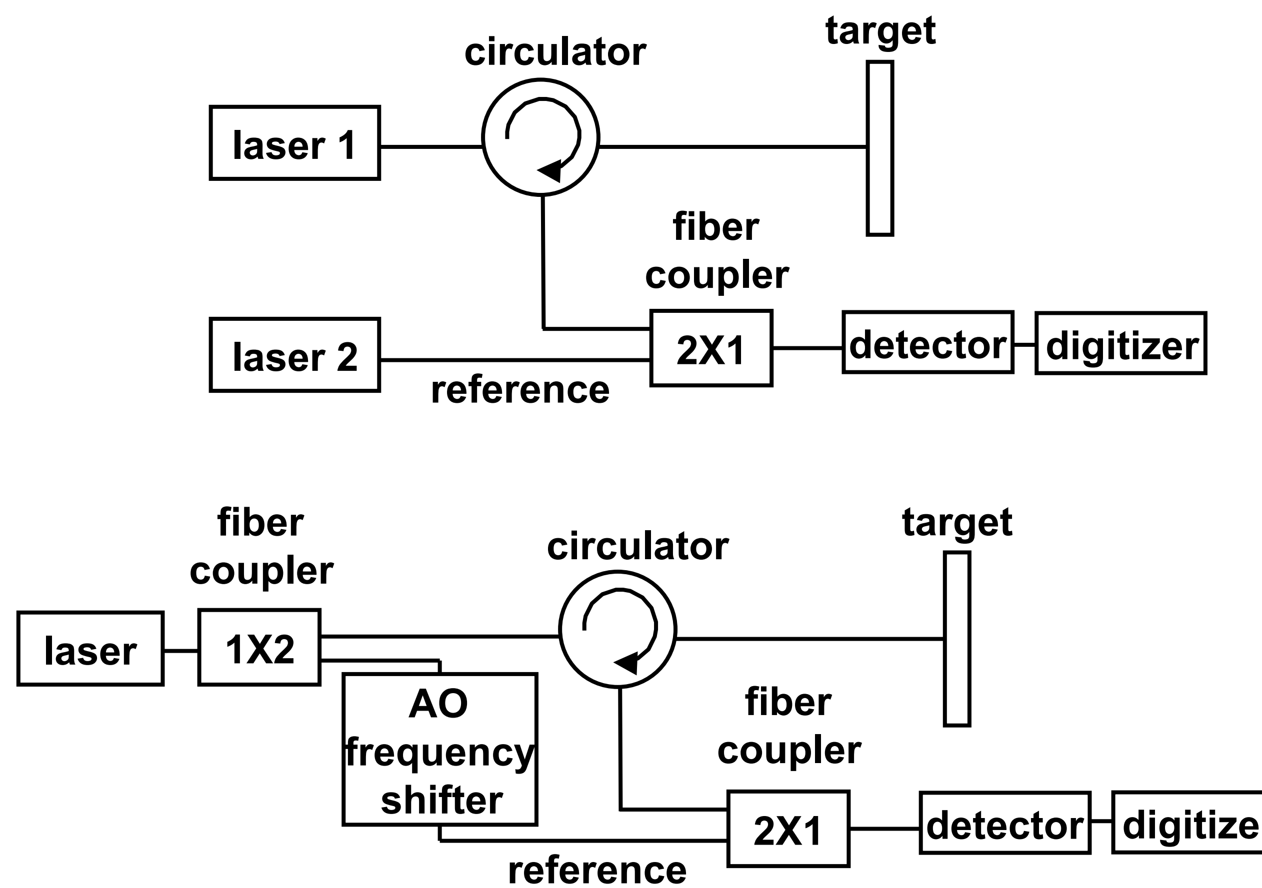
Frequency-conversion PDV

- Two wavelengths
  - One illuminates target
  - One serves a reference
- Up/down conversion
  - Frequency may increase or decrease with increasing velocity, depending on configuration
  - Can provide direction information
- This is my favorite approach
  - Works at any velocity
  - Utilizes the power of the FFT



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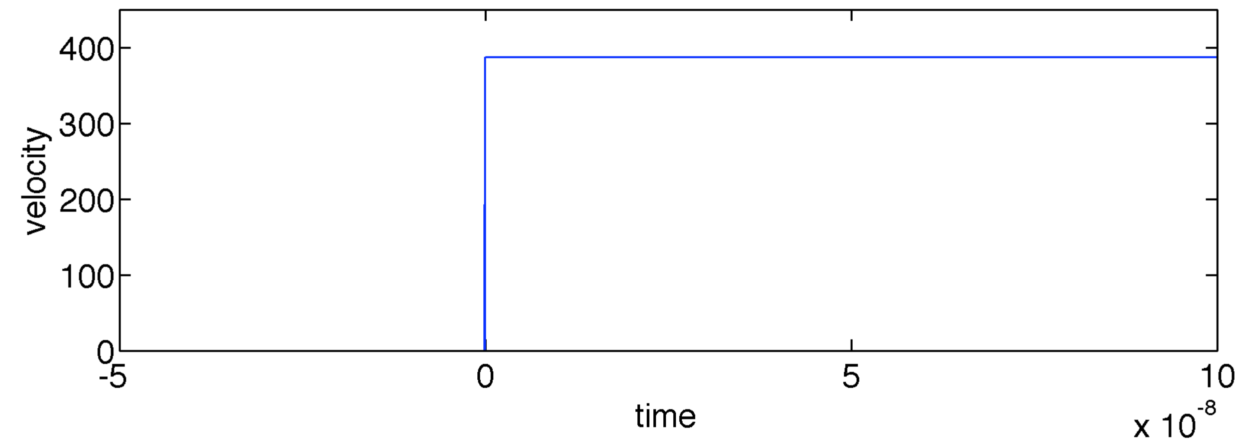
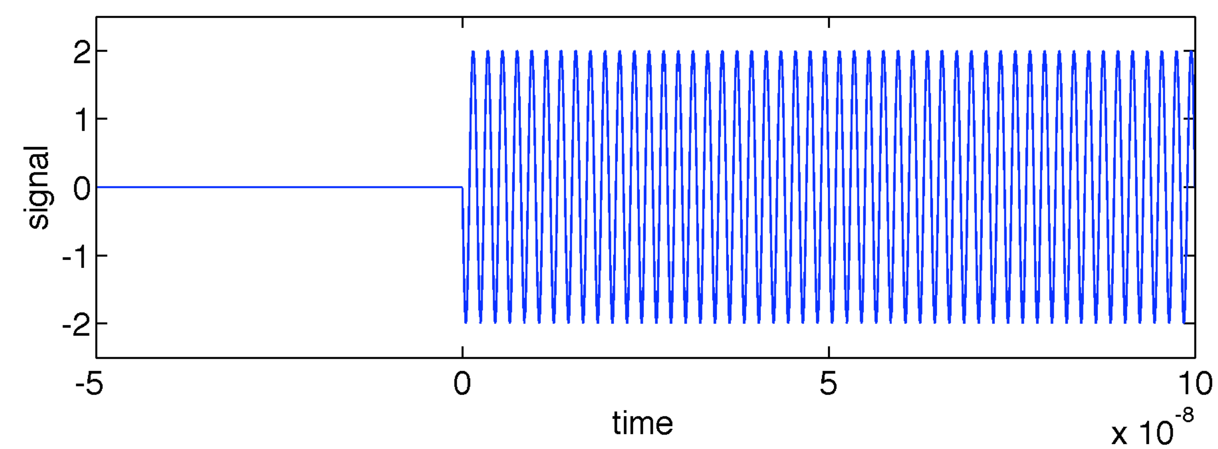
A simple example

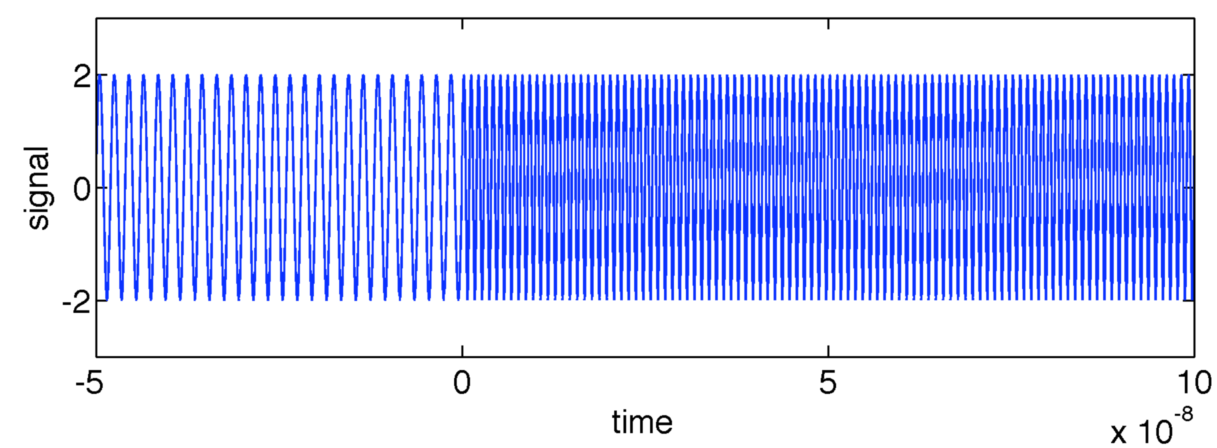
- Consider a velocity step



- Conventional PDV
  - Constant signal at rest



- Frequency-conversion PDV



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PDV approximation

Suppose velocity changes slowly over some small duration.

$$x(t) \approx x(\bar{t}) + \bar{v} \times (t - \bar{t})$$

The optical signal in this duration would be harmonic:

$$I(t) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left[\bar{\Phi} + 2\pi\left(\frac{2\bar{v}}{\lambda_0}\right) t\right]$$

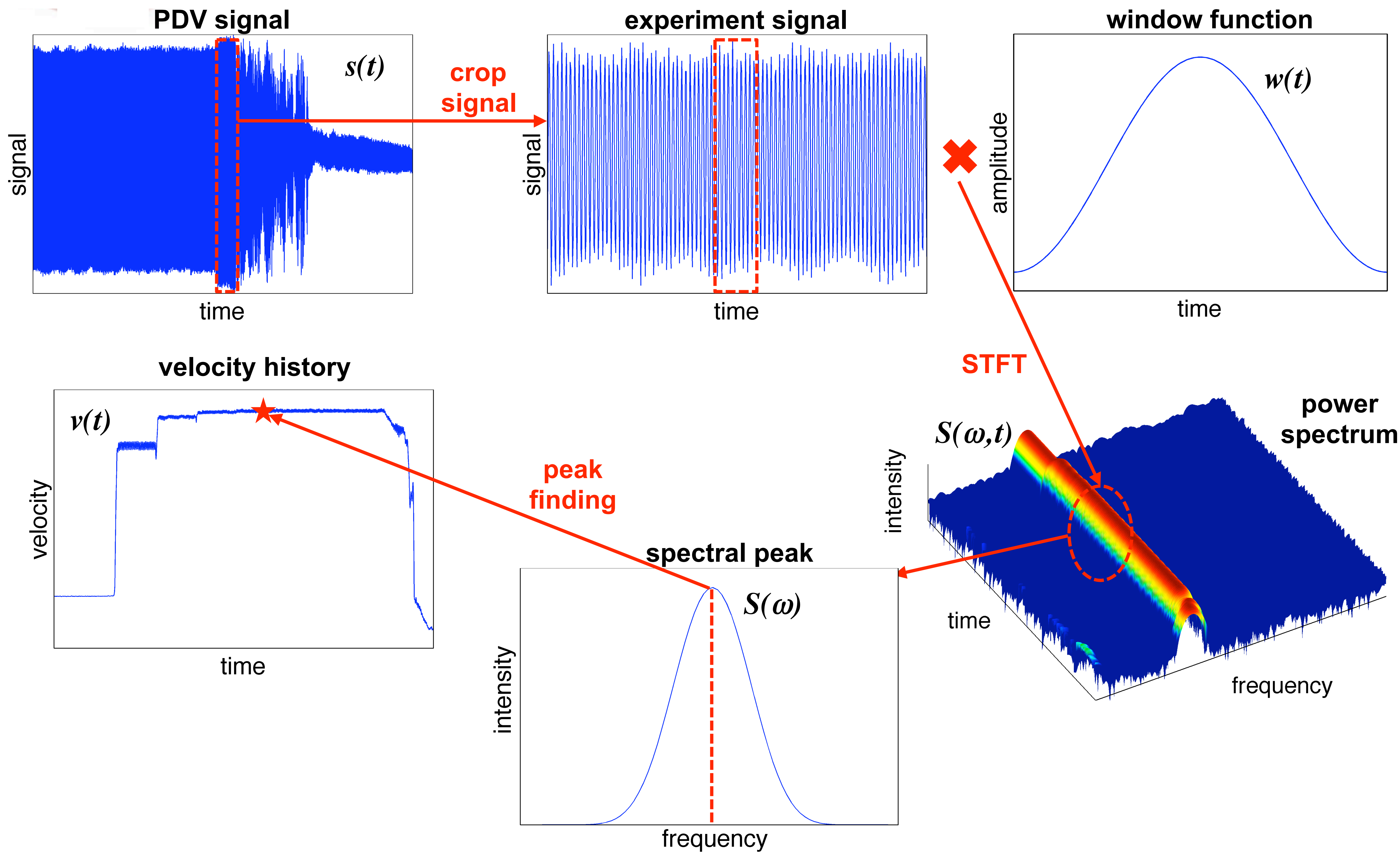
with a beat frequency proportional to velocity.

This frequency can be determined with a short-time Fourier transform (STFT).

$$S(f, \bar{t}) = \int_{-\infty}^{\infty} s(t) w(t - \bar{t})\ e^{-2\pi i f t}\ dt$$

Window w(t) selects regions in signal s(t).

Analysis overview



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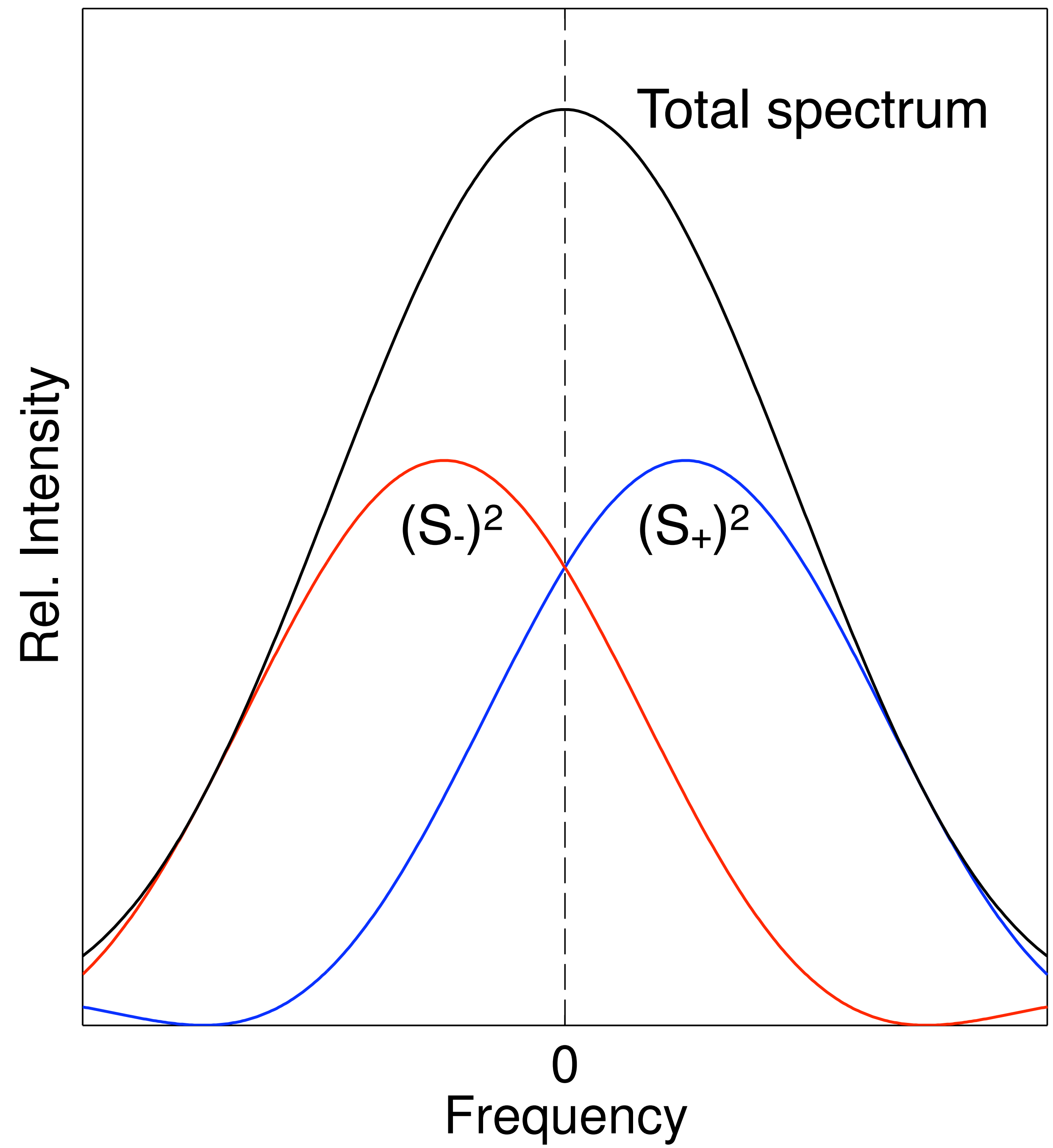
An important detail...

- Real signals contain positive and negative frequency components
- These components have considerable overlap at low velocity
- Separating peaks prevents overlap
  - Locating the positive peak is more accurate/precise
  - Occurs with large velocities and/or frequency conversion



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Things to be aware of

- Frequency response is king with PDV
  - Use the fastest detectors possible
    - Step response not particularly important
  - One fast digitizer is better than several slow digitizers
  - Beware of Nyquist requirement (aliasing)!

- Angle polished (8^o) connections are crucial
  - This is common, but not universal

- All windows should be anti-reflection coated
  - PDV can detect very weak reflections
  - These reflections can effect primary signal, particularly for short analysis durations
  - AR coating to the 0.05% level is recommended

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VISAR versus PDV

What diagnostic should I use?

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General comments

- Each diagnostic has merits in certain areas
  - Ejecta (reflector comes apart)
    - PDV works
    - VISAR does not
  - Extreme velocities (>20 km/s, often open beam)
    - VISAR works
    - PDV does not (yet)

- What about continuous velocity measurements below ~15 km/s?
  - Structured wave profiles: shocks, ramps, and everything in between

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Obvious differences

- VISAR:
  - Is established and trusted
  - Can use low bandwidth equipment (digitizers) to cover any velocity region
  - Requires careful system characterization
  - May require frequent maintenance

- PDV:
  - Is simple to build and operate (fiber)
  - Can be made very compact
  - Has very few hardware adjustments (delay, etc.)
  - Is robust to multiple velocities, extreme light variations (40-60 dB), and digitizer clipping
  - Often requires high bandwidth equipment

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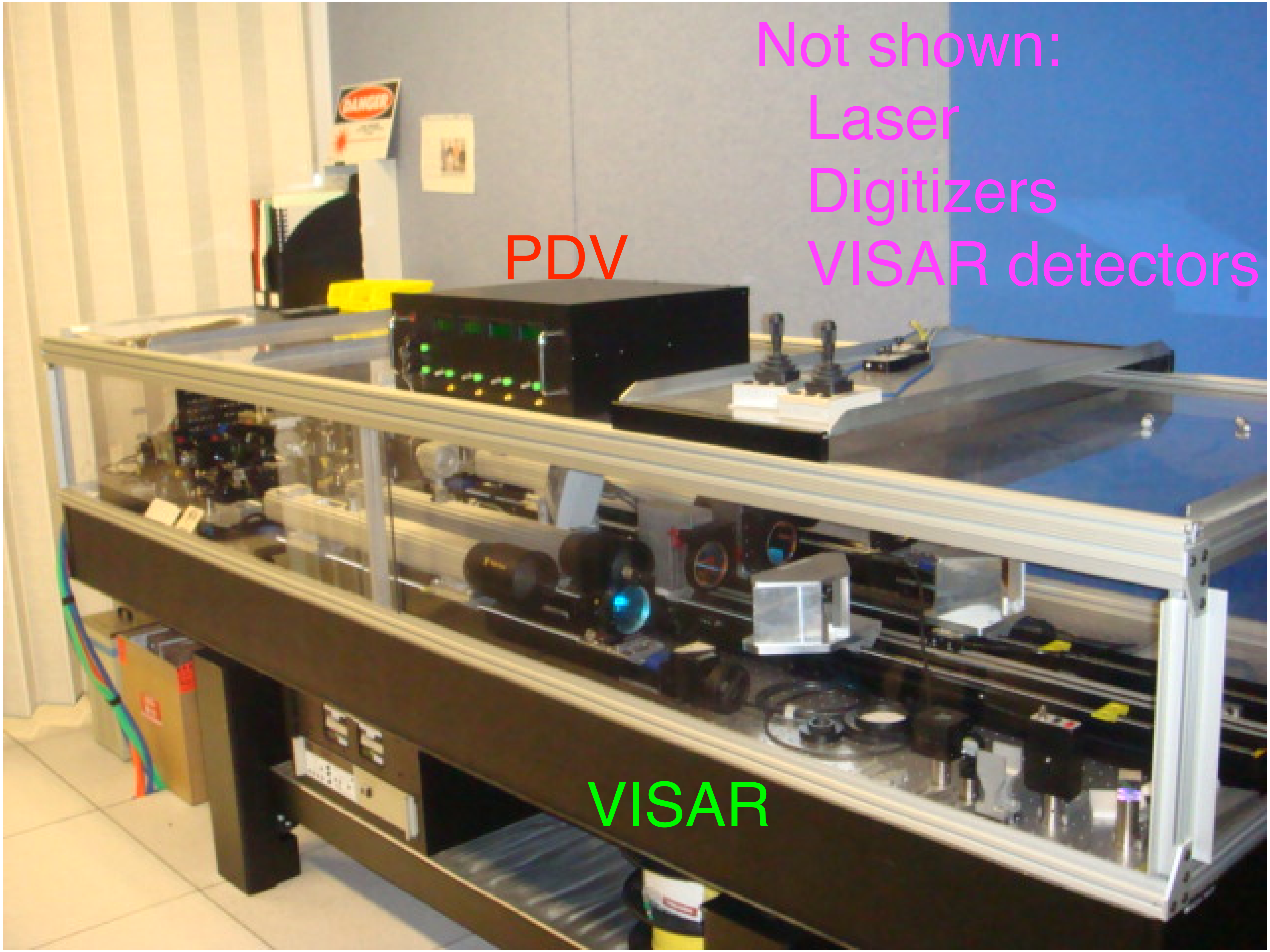
Size comparison



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PDV myths

- PDV is ill-suited for modest velocities (<1 km/s)
  - Example: 100 m/s
    - Beat frequency: 129 MHz (7.75 ns period)
    - Limiting time resolution is no less than 8 ns
    - Things are even worse at lower velocities
    - PDV is not good for low-velocity transients (QED)
  - Frequency shifting avoids this problem
- The uncertainty principle **severely** limits PDV resolution
  - Min. velocity-time width product is constant
  - Peak position can be determined better than the width
- PDV is less sensitive than VISAR because it operates at a longer wavelength
  - This is true but frequency can be measured **very** accurately

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The uncertainty principle

- Displacement measurements trade time and velocity resolution
- VISAR
  - Ideal fringe resolution is ~2%
  - Delay time sets an intrinsic resolution limit
    - 1 ns delay >> 2-3 m/s resolution
- PDV
  - Product of time-velocity widths: $$\sigma_v \times \tau \geq \frac{\lambda_0}{8\pi}$$
    - 1 ns >> 62 m/s!!
  - You can do much better:

$$\sigma_v \times \tau = \sqrt{\frac{6}{f_s \tau}} \frac{\lambda_0 \, \sigma}{2\pi}$$

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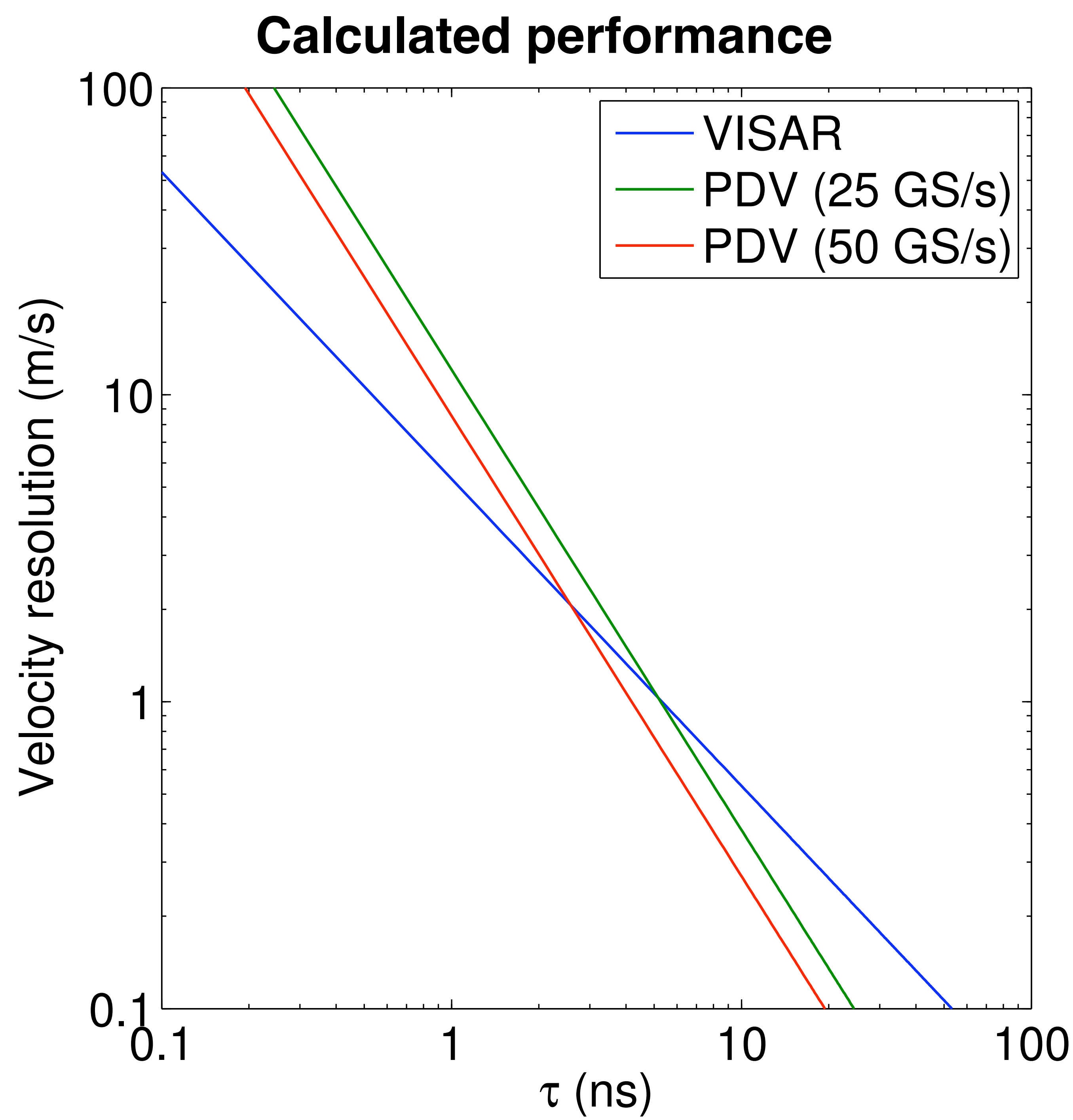
Theoretical comparison

- Consider
  - 532 nm VISAR, 2% fringe resolution
  - 1550 nm PDV, 10% signal noise (two sample rates)



- PDV matches VISAR resolution at τ=
  - 5.2 ns (25 GS/s)
  - 2.6 ns (50 GS/s)

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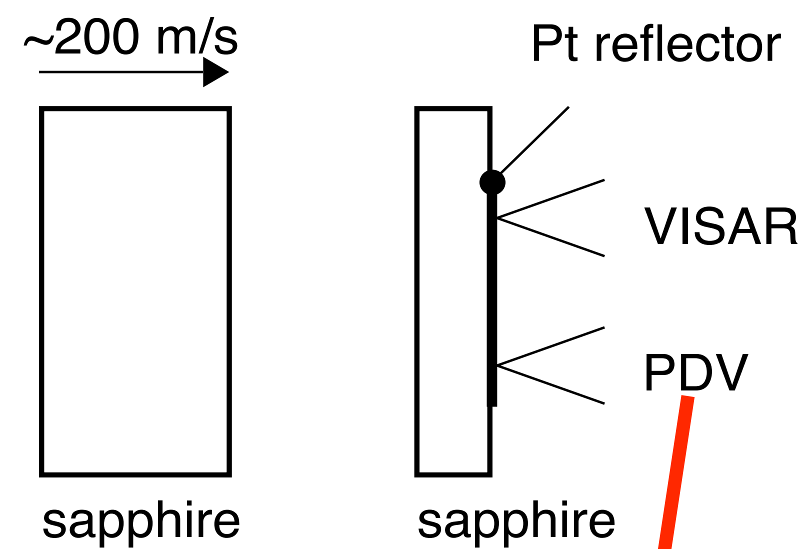
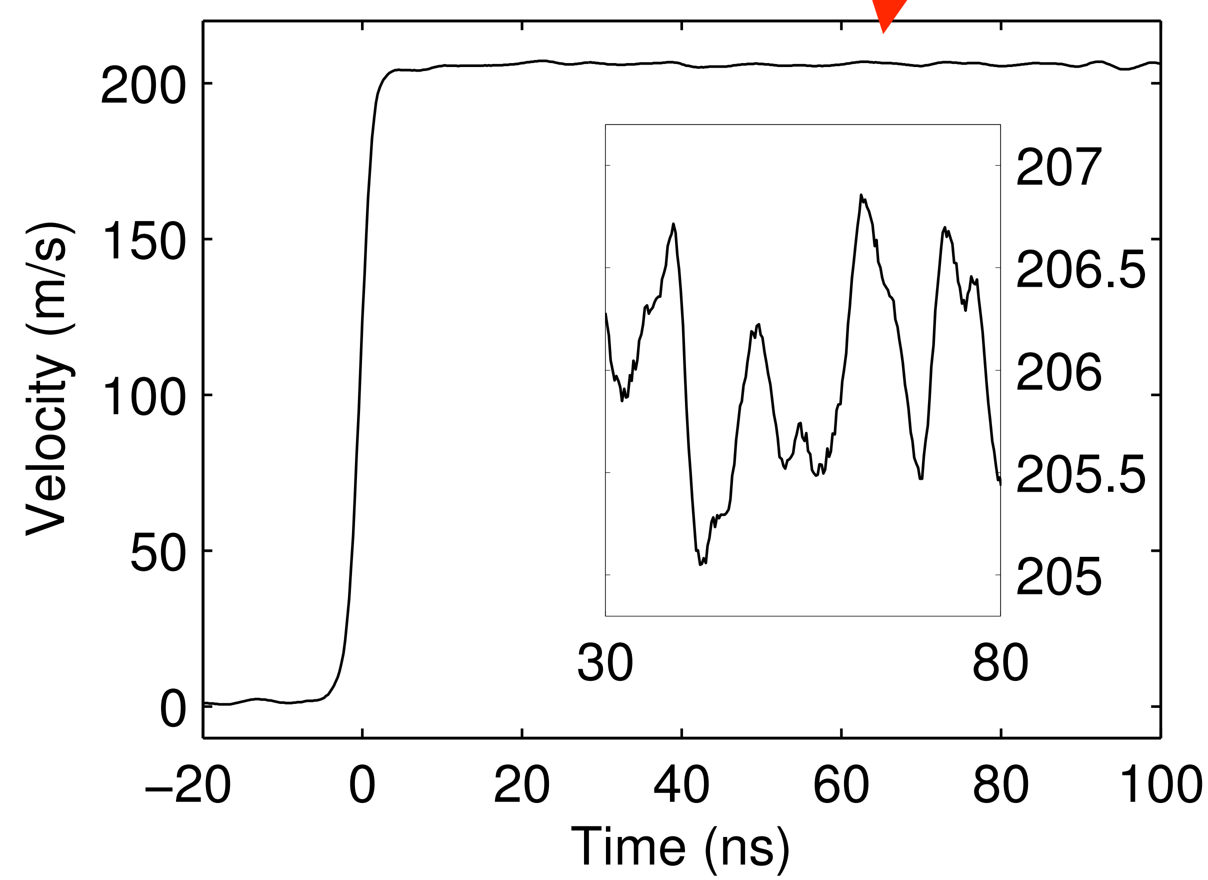
Experimental test

- Symmetric impact with velocimetry at the free surface
- Compared PDV with air-delay VISAR (14 m/s VPF) and shorting pins
- PDV precision trends consistent with analytic limit





Diagnostic	Time scale (ns)	Velocity change (m/s)
Pins	>1000	206.6 (1.1)
VISAR	19	206.11 (0.28)
PDV	19	205.95 (0.32)
PDV	10	205.93 (0.64)
PDV	1	206 (21)

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Which is better?

- VISAR beats PDV performance on short time scales. However:
  - VISAR: 4-8 signals, PDV: 1 signal
  - PDV rise time (10-90%) is <1/2 of VISAR for a given τ
  - VISAR fringe resolution is often much worse than 2%

- PDV requires faster digitizers, but fewer channels/probe
  - Cost per probe is fairly similar

- It's probably not worthwhile building VISAR systems:
  - With delay times larger than 3-5 ns
  - At 1550 nm (loses the wavelength advantage)

- Starting from scratch, PDV is generally better than VISAR below 10 km/s (some caveats)

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Summary

- Velocimetry is the most common diagnostic in dynamic compression research
  - Straightforward to measure and interpret

- Optical interferometry encodes reflector displacement into a measurable electric signal
  - VISAR: signal changes when velocity changes
  - PDV: signal changes when position changes

- Each diagnostic has its merits
  - VISAR measures any velocity with modest bandwidth
  - PDV requires higher bandwidth, but has many compelling advantages

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Handout summary

- "Foundations of VISAR analysis", SAND2006-1950
  - Everything you ever wanted to know (and perhaps more) about VISAR
  - Some relevance beyond VISAR (window corrections, 2D motion, etc.)

- "SIRHEN: a data reduction program for photonic Doppler velocimetry measurements", SAND2010-3628
  - PDV theory (with frequency conversion)
  - Analysis implemented by SIRHEN (copyright pending)

- "Velocimetry signal synthesis with fringen", SAND2011-0582
  - VISAR/PDV measurement details

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