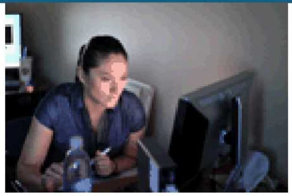
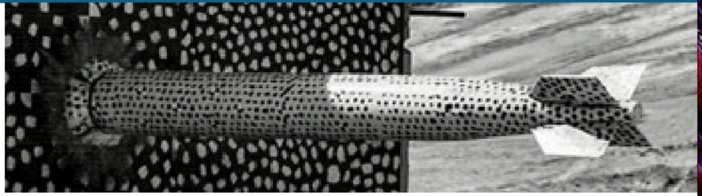
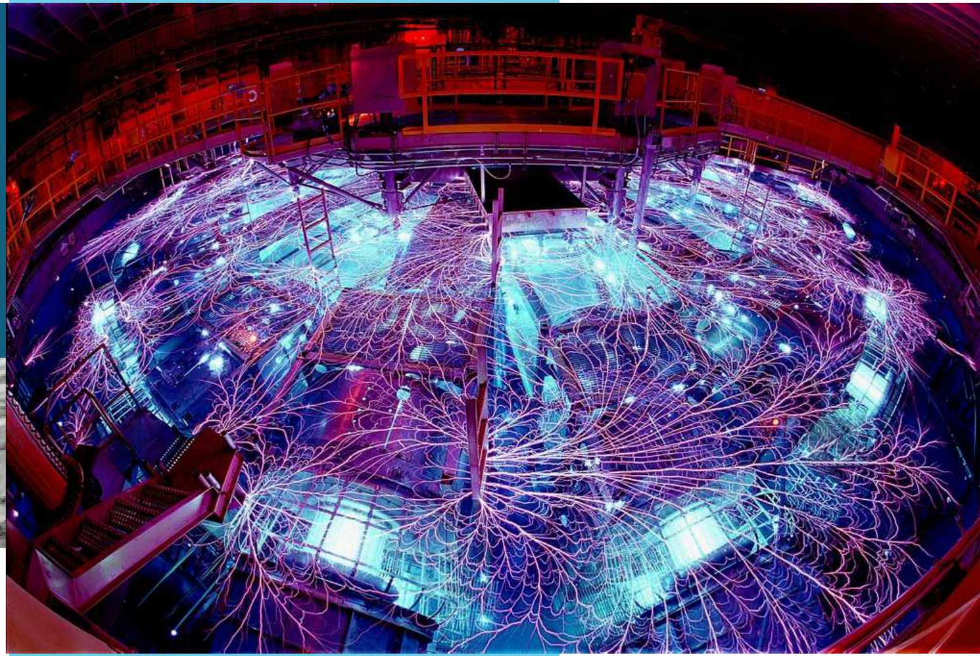
SAND2020-7287PE

Optical velocimetry







Presented by:

Daniel Dolan

Dynamic Material Properties

Pulsed Power Division

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Overview

Background
- Why we measure velocity
- Transit time measurements

Optical Doppler shift measurements
- "Displacement" interferometry
- "Velocity" interferometry (aka VISAR)

Photonic Doppler Velocimetry (PDV)
- Technology overview
- Theory
- Examples

Why do we measure velocity?

Why do we measure velocity?

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

$$P = \rho_0 U_s u_p$$

Because we can:

- With fast time resolution (ns and faster)
- With high accuracy (1% or better)
- In harsh conditions (impact, detonation, etc.)
- At many locations simultaneously
- Directly compare with wave codes

Pressure/density linked to jump conditions:

- Shock velocity U_s
- Particle velocity u_p
- Most tabulated data based on this type of measurement

IRON

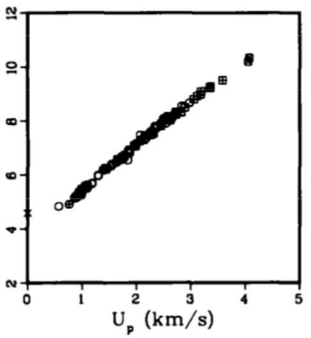
Average ρ_0 = 7.856 g/cm³.

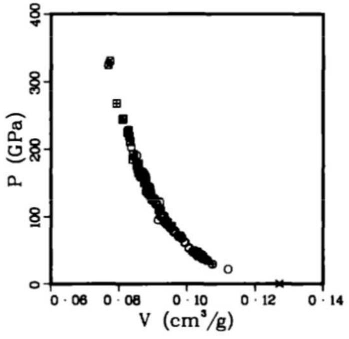
Sound velocities longitudinal 5.94 km/s.
shear 3.26 km/s.

References 4, 5, 6, 11, 12, 13, 17, 22

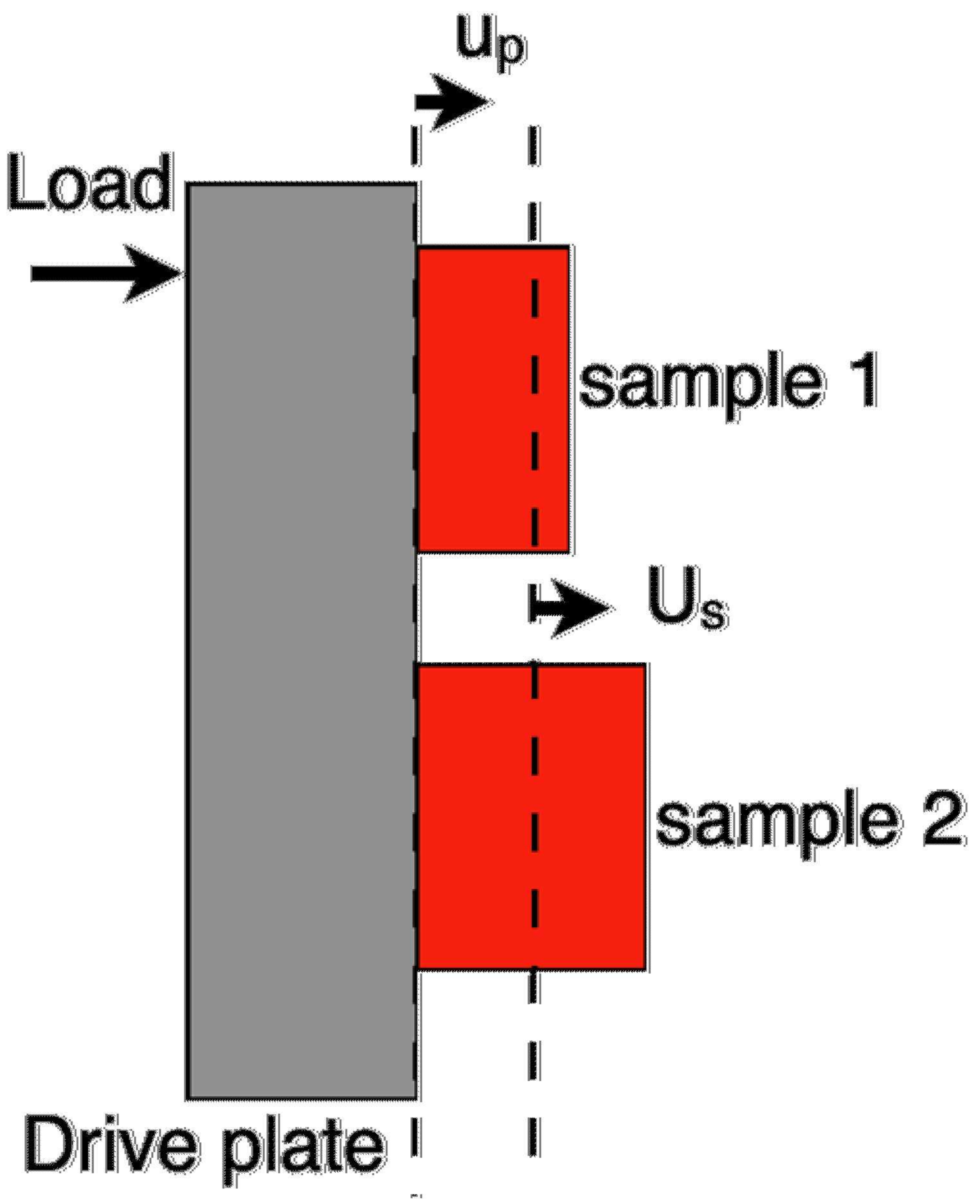
ρ_0 (g/cm³)	U_s (km/s)	U_p (km/s)	P (GPa)	V (cm³/g)	ρ (g/cm³)	V/Vo	Exp
7.870	4.595	0.000	0.000	.1271	7.870	1.000	ssp ×
7.861	4.838	.573	21.792	.1121	8.917	.882	im1 ○
7.850	4.913	.763	29.427	.1076	9.293	.845	sf1 ⊕
7.840	5.144	.867	34.965	.1061	9.429	.831	sf1 ⊕
7.840	5.147	.867	34.986	.1061	9.428	.832	sf1 ⊕
7.840	5.168	.876	35.493	.1059	9.440	.830	sf1 ⊕
7.850	5.190	.881	35.893	.1058	9.455	.830	sf1 ⊕
7.840	5.166	.884	35.803	.1057	9.459	.829	sf1 ⊕
7.882	5.225	.903	37.189	.1049	9.529	.827	im1 ○
7.882	5.172	.906	36.934	.1046	9.556	.825	im1 ○
7.850	5.328	.948	39.650	.1047	9.549	.822	sp1 ⊞
7.850	5.360	.952	40.056	.1048	9.545	.822	sf1 ⊕
7.840	5.393	.968	40.928	.1047	9.555	.821	im1 ○
7.840	5.373	.969	40.818	.1045	9.565	.820	im1 ○
7.882	5.339	.984	41.409	.1035	9.663	.816	im1 ○
7.840	5.408	.988	41.890	.1042	9.592	.817	im1 ○
7.864	5.252	.989	40.847	.1032	9.688	.812	im1 ○
7.850	5.443	.995	42.514	.1041	9.606	.817	sf1 ⊕
7.843	5.458	.998	42.721	.1042	9.598	.817	sp1 ⊞

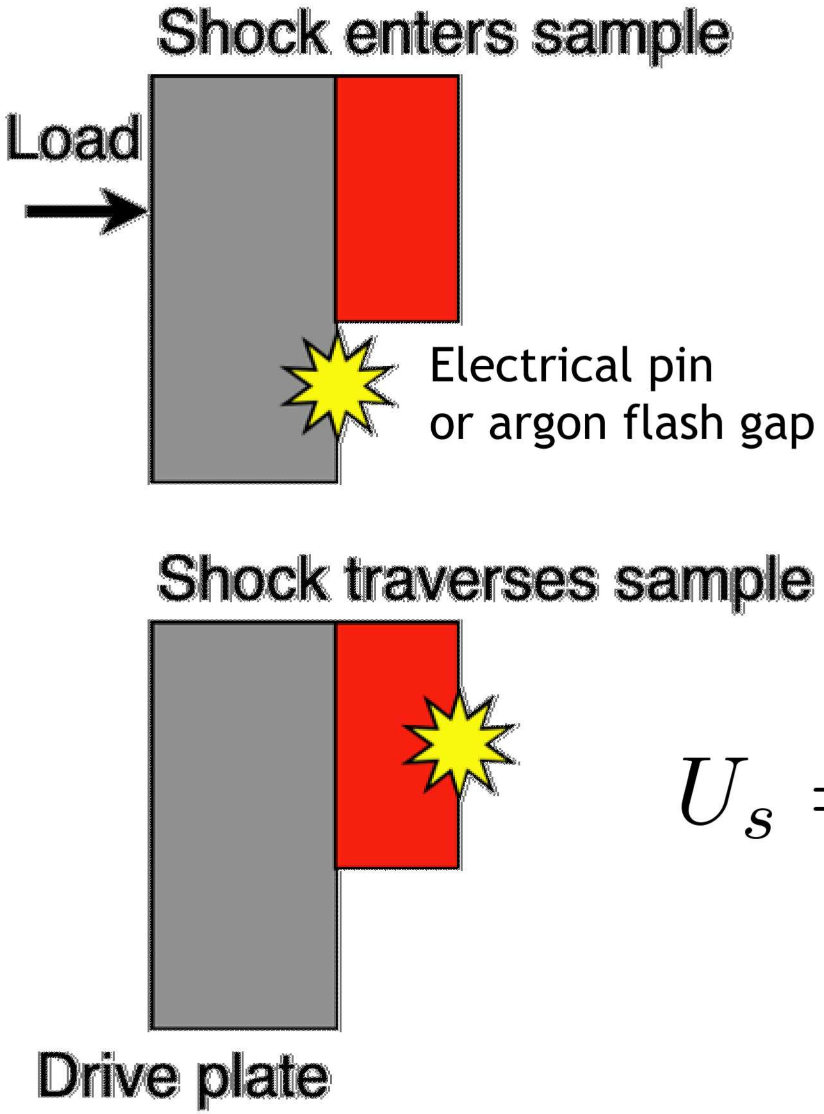
(Continued)





A traditional shock experiment





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

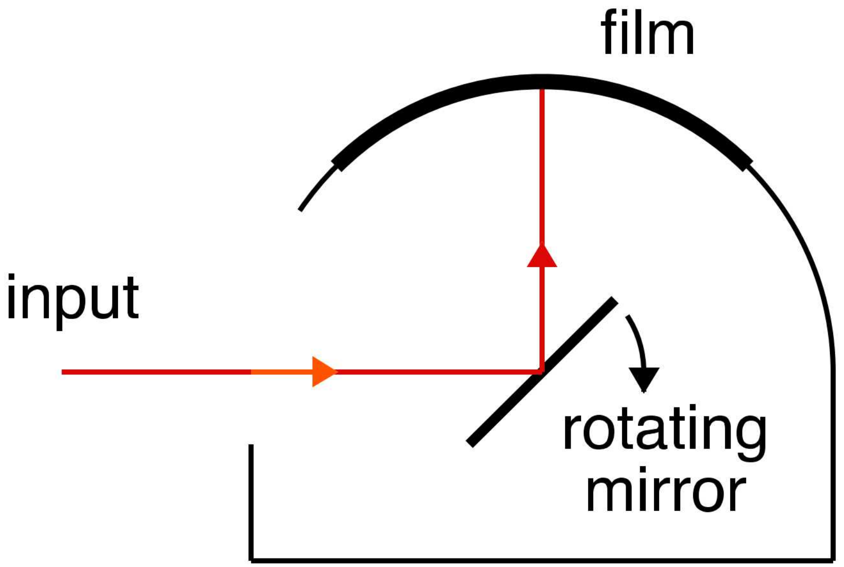
Recording bandwidth

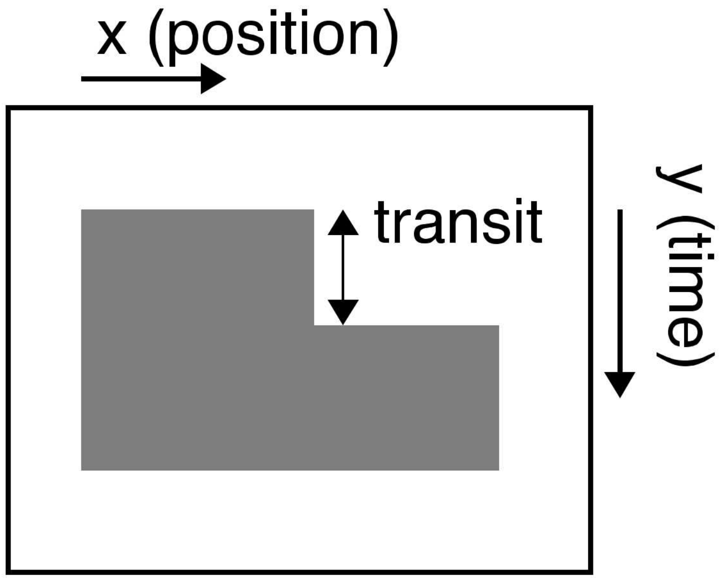
Rotating mirror streak cameras for Ar flash

- ~100 MHz recording bandwidth
- Rotation must be known precisely
- Film distortion is a problem
- Largely replaced by streak tubes
  - >1 GHz bandwidth

Electrical shorting pins became more common with faster oscilloscopes

- 10-24 MHz from late 1940s to 1960
- ~1000 MHz available in 1960
- Digitizers transition 1960-1995
  - 1995-2005 >1 GHz
  - 2005-2015 >10 GHz





Clever pin use reveals wave structure

- Bancroft et al., J. Appl Phys **27,** 291 (1956).
- Most of us are **not** that clever

POLYMORPHISM OF

: meets a retreating rarefaction in general t
:crease the shock velocity.‡ It will be assumed
:ffects due to the elastic wave are negligibl
D_{32}' can be determined from the coordinat
: 4. It may easily be shown that

$$t_4=\frac{d_3-d_5+t_3D_c'+t_5D_d'}{D_c'+D_d'}$$

his same conclusion may be reached in a variety o
ther ways.
An estimate of D_d' is also fairly clear. The amplitud
f the disturbance at this stage is less than the ampli
ıde to which D_{21} applies; accordingly one might expec
s velocity to be somewhat lower than D_{21}. Howeve
:sults from other experiments at shock pressures belo
.13 megabar include velocities of propagation whic
o not clearly differ from D_{21}. Therefore it seem
:asonable to assume that $D_d=D_{21}$, so that $D_d'=D$
-$2u_2$. Thus Eqs. (10) become

$$t_4=\frac{d_3-d_5+D_{21}(t_5+t_3)+2u_2(t_5-t_3)}{2D_{21}} \quad (14$$

$$d_4=d_3-(D_{21}-2u_2)(t_4-t_3).$$

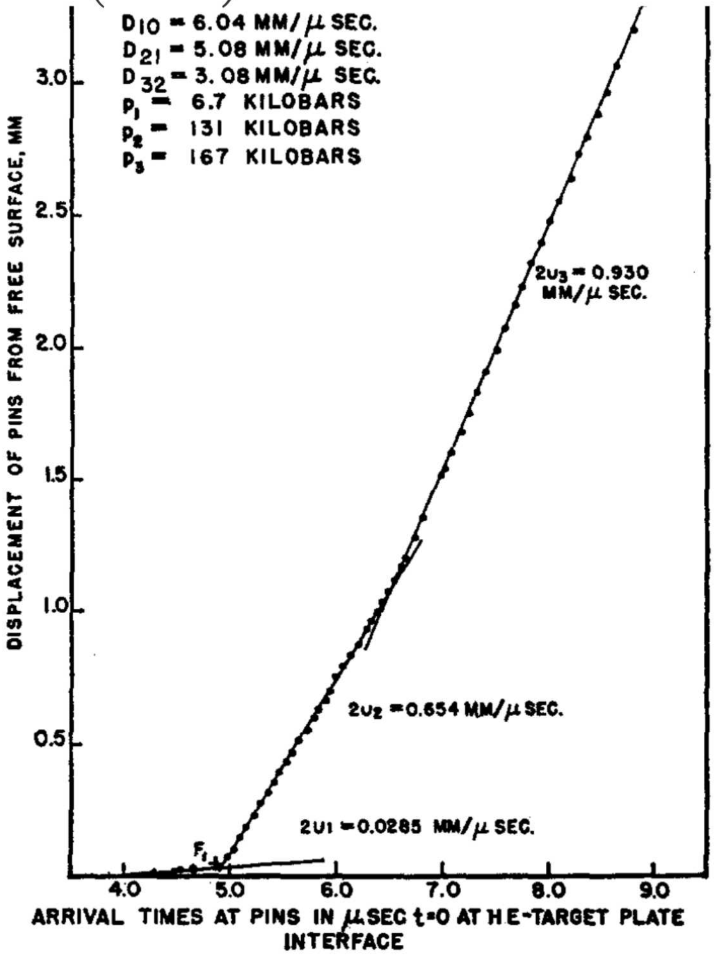


FIG. 8. Displacement-time curve for Exp. 5.
See text for analysis.

shock system was detected. The pin array was simple

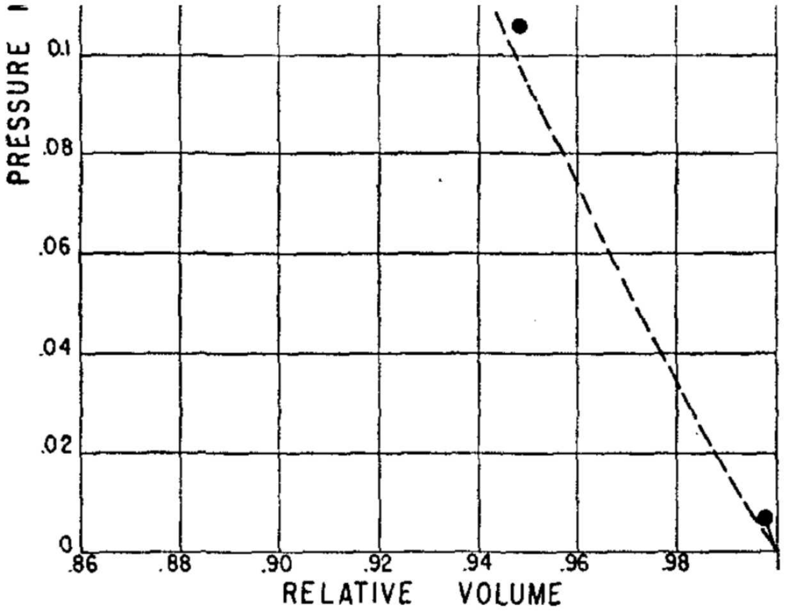


FIG. 10. Relative volume v/v_0 as a function of pressure. Cir
w points computed from measurement of shock wave and
face velocities of Armco iron. The dashed curve is an ex
ation of Bridgman's data [with the help of Eq. (21)].

gabar, which is negligible. Accordingly the aver
ta may be used directly for computing a value
in the isentropic equation of state

$$p_s=\alpha_s\mu+\beta_s\mu^2, \quad ($$

ere $\mu=(\rho/\rho_0)-1$ is the compression. Gorans

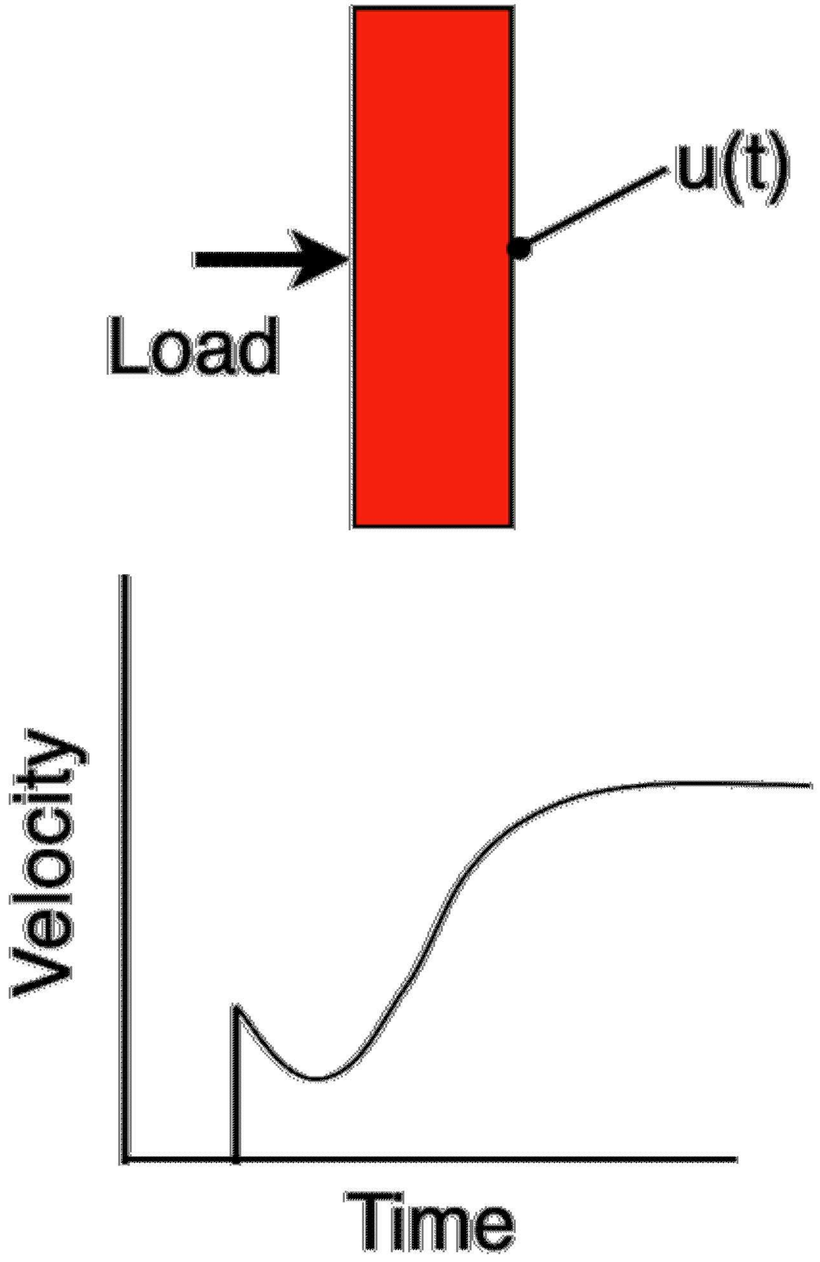
Non-steady waves

Mechanical waves often contain a lot of structure

- Inelastic compression
- Phase transitions
- Chemical reactions
- Ramp wave (release and/or tailored)

Structure difficult to extract from transit time measurements

- Real-time velocity diagnostics are needed



Optical velocimetry

There are many ways to track motion with light

Optical emission: compression creates light
- "Passive" shock breakout

Optical reflection (amplitude or direction)
- "Active" shock breakout
- Beam deflection requires special geometry and specular surfaces

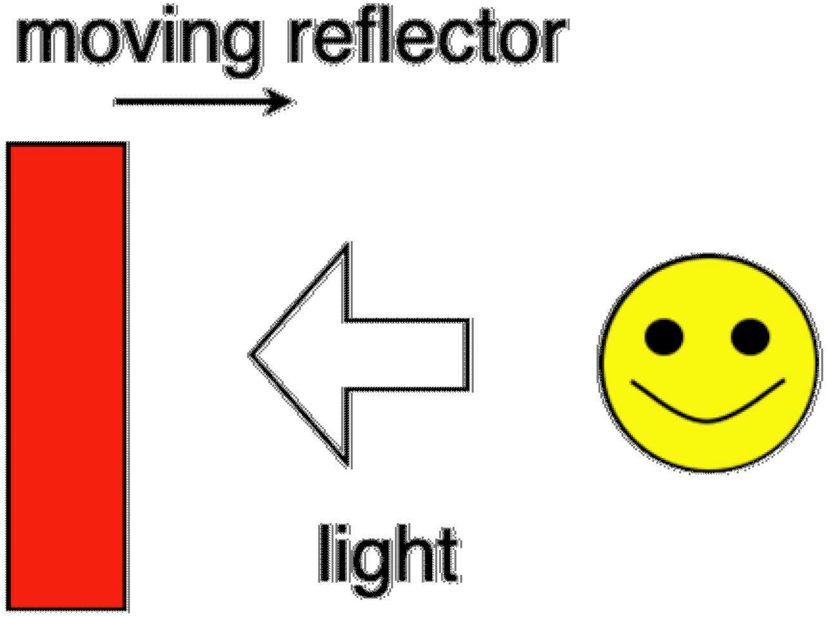
Optical phase techniques are more flexible
- Optical phase "wags" the electric field
- Frequency is the rate of optical phase change
- Wavelength is the reciprocal of frequency
  - 532 nm is 564 THz (1-2 fs)

$$E(t) = A(t)\cos\phi(t)$$

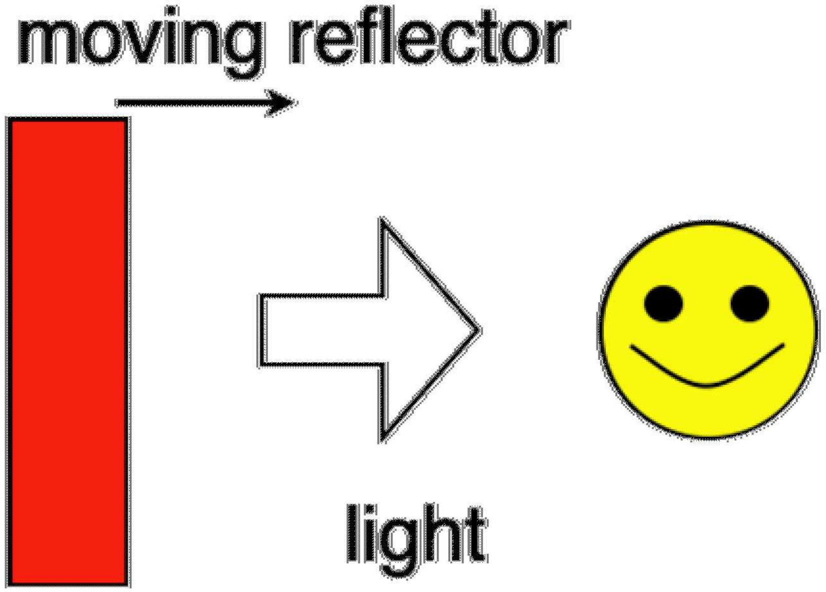
$$\phi(t) \sim 2\pi f t$$

$$f = \frac{c_0}{\lambda}$$

The optical Doppler effect



Observer sees: λ_0
Reflector sees: λ'



Reflected light: λ'
Observer sees: λ

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

Non-relativistic motion
(100 km/s is 0.03% c_0)

Optical velocimetry usually means optical interferometry

Electric field cannot be measured directly

- Direction flips many times over detector response

Wavelength changes cannot be resolved with grating spectrometers

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

Two-beam interferometry is the most common approach

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

- Fields add coherently
- Intensity (power/area) is time-averaged square of electric field

Some terminology

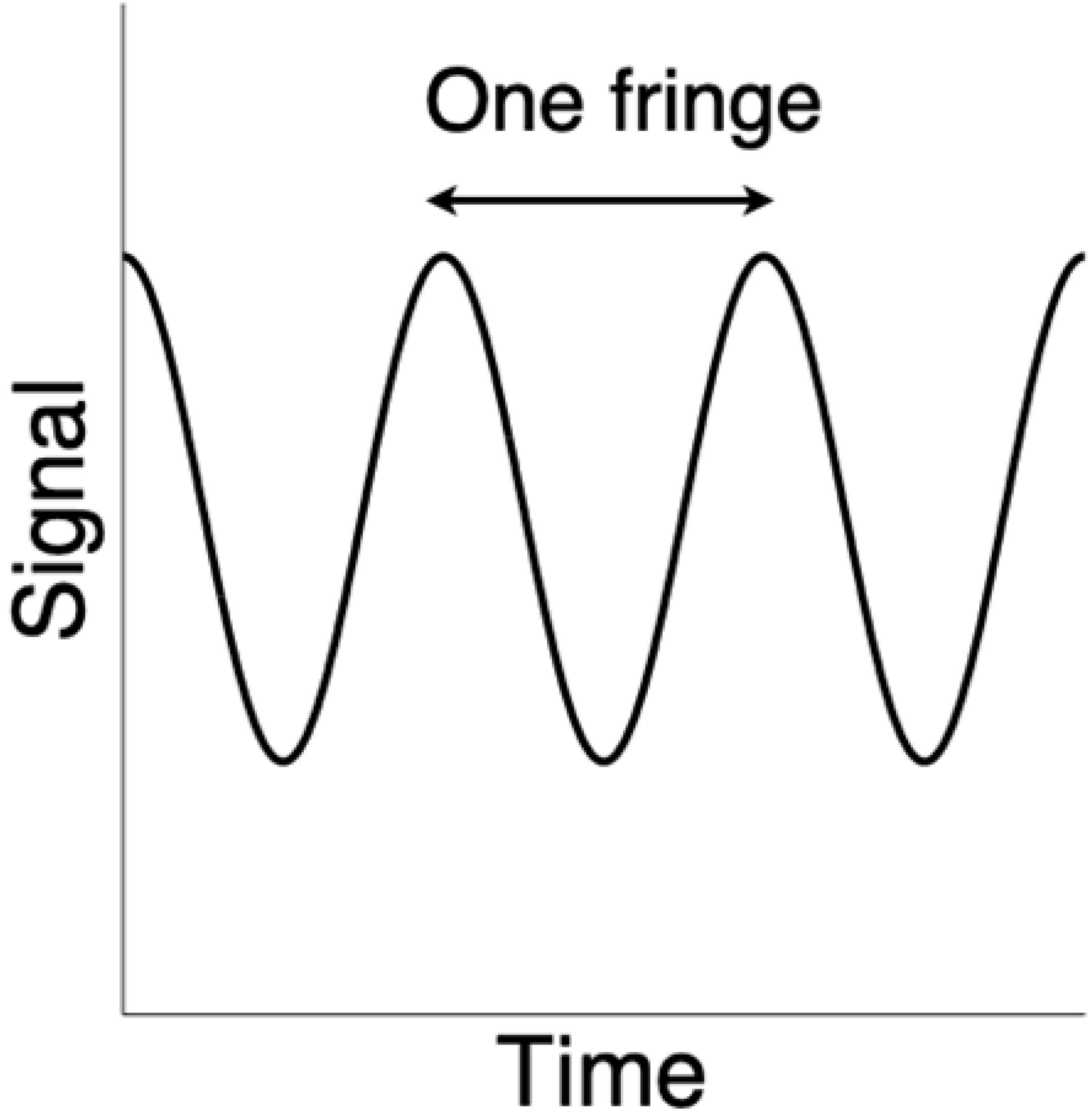
Fringe shift

- Phase difference scaled by 2π
- Same as signal cycles

Beat/fringe frequency

- Rate of signal cycles
- Not the same as optical frequency

We can only measure signal cosine functions, not the electric field cosine function



A historical detour

L.M. Barker, Experimental Mechanics **12**, 209 (1972).

Sandia displacement interferometer

- Michelson configuration
- 1 fringe = 1/2 wavelength motion

Problems

- Mirror finish required
  - Surface often changes at shock breakout
- Limited velocity range
  - 1 km/s is 3.2 GHz at 632.8 nm
  - No oscilliscope could follow such frequencies in the 1970s

ave Research

ibes

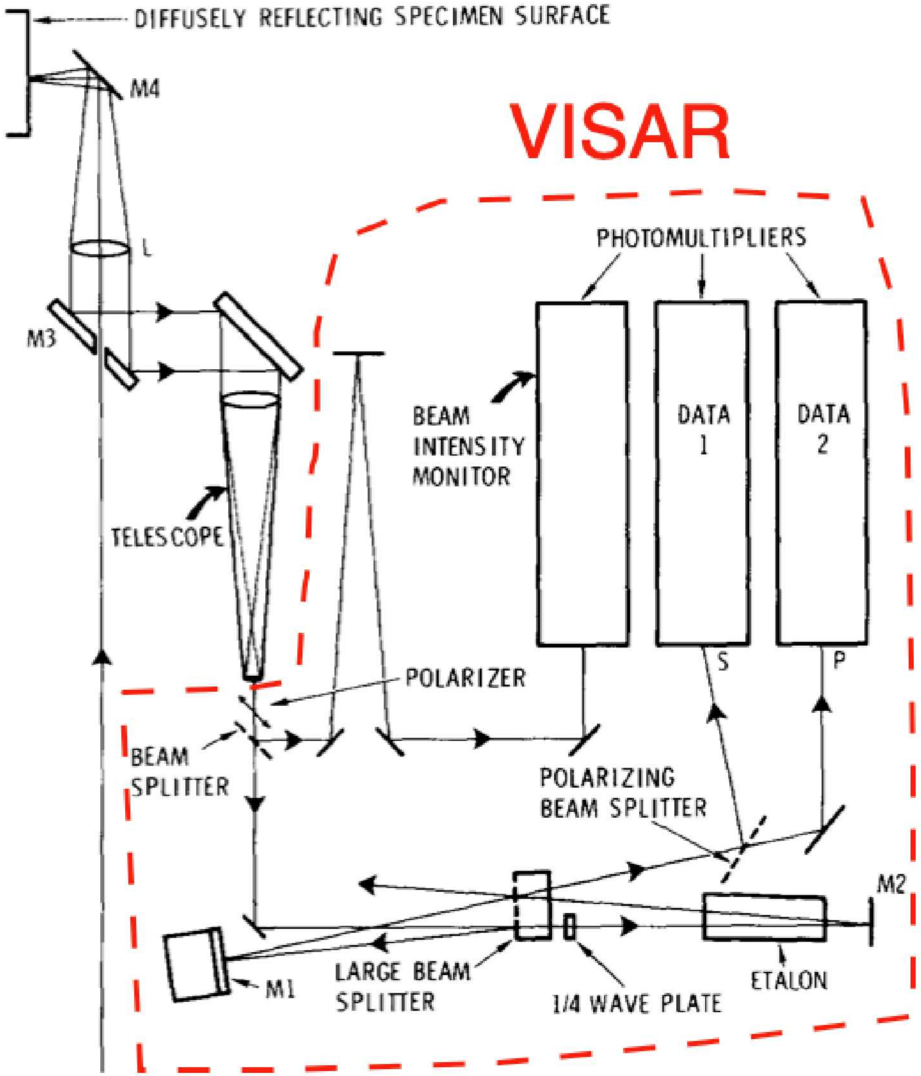
Velocity Interferometer System for Any Reflector (VISAR)

VISAR solves the bandwidth problem

Barker and Hollenbach, J. Appl. Phys. **43**, 4669 (1972).

Doppler-shifted light mixed with a time-shifted version of itself
- Avoids large steady-state frequencies

Etalon allows diffuse reflectors
- "Any Reflector"



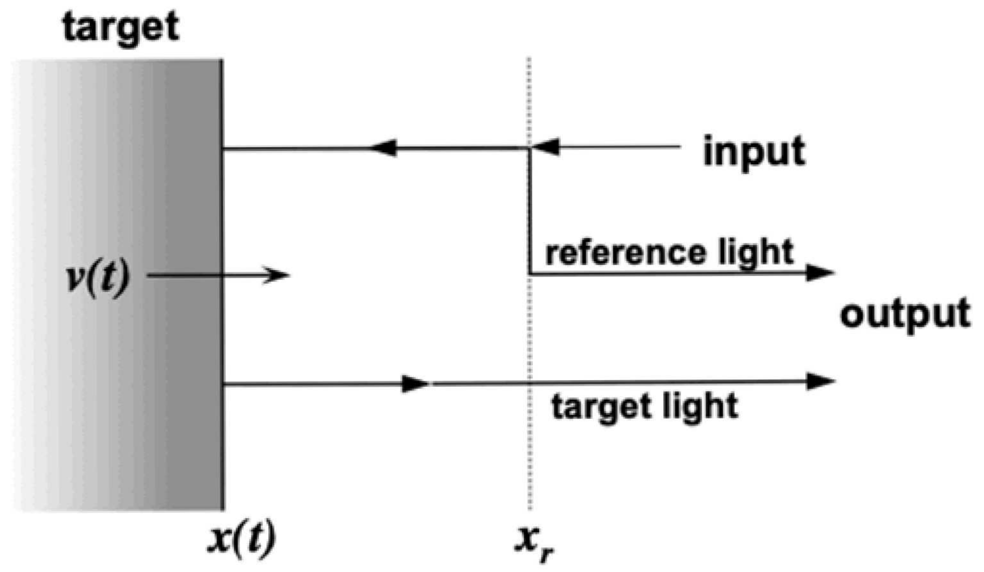
Continuous wave profile of iron.
Barker and Hollenbach,
J. Appl. Phys. **45**, 4872 (1974).

'elocities in mm/μsec, accelerations in mm/μsec², str

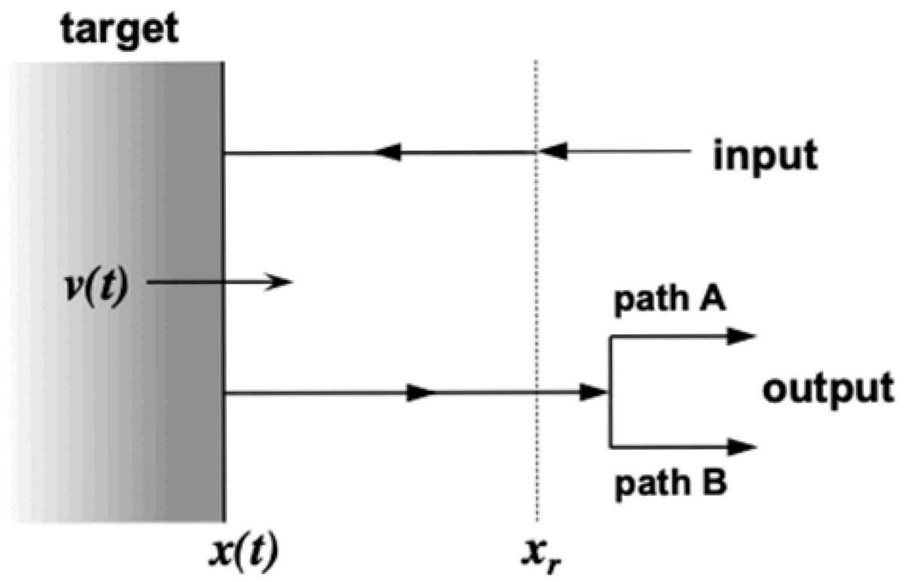
u_{fm}[a] / u_m	u_{fs}[a] atop P1 wave	Stress atop P1 wave	Peak accel. in P1 wave[b]	Peak accel. in P2 wave[c]
1.982	0.645	13.15	...	1.52
1.976	0.652	13.30	...	4.00
1.971	0.635	12.92	...	0.85
1.968	0.637	12.96	...	4.66
1.972	0.653	13.32	...	7.86
1.978	0.667	13.60	...	26.1
1.964	0.634	12.90	...	5.29
1.967	0.640	13.02	...	14.8
1.976	...	...	...	...
1.971	...	...	...	...
...	...	...	...	...
1.969	...	...	...	...

What is the difference?

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



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



*The VISAR approximation

IF velocity changes slowly compared to the delay time:

- Fringe shift scales with velocity (approximation)
- Exact behavior is more complex
  - Explicitly depends on delay time
  - Dolan and Specht, JDBM **3**, 407 (2017).

Sensitivity defined by wavelength and delay time

- Fringe constant or Velocity Per Fringe (VPF)
- ~50-5000 m/s per fringe

$$F = \left(\frac{2\tau}{\lambda_0}\right) u$$

$$VPF = \frac{\lambda_0}{2\tau}$$

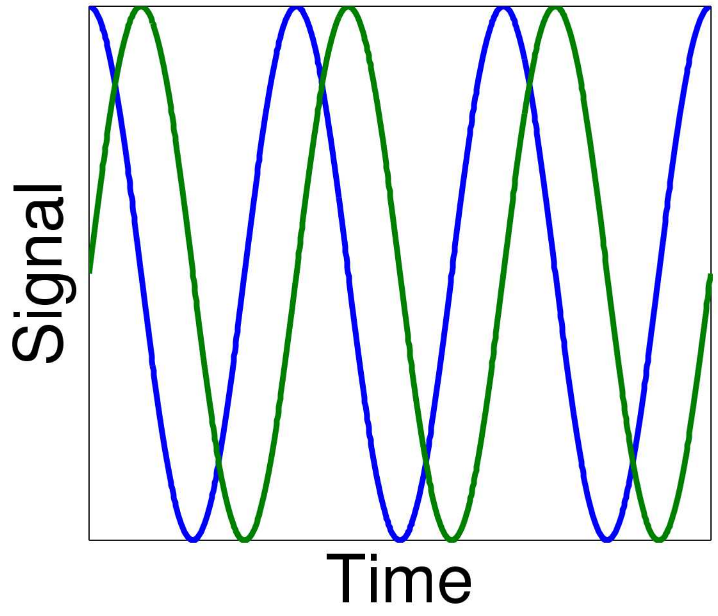
$$\tau \approx 0.1\text{–}10 \text{ ns}$$

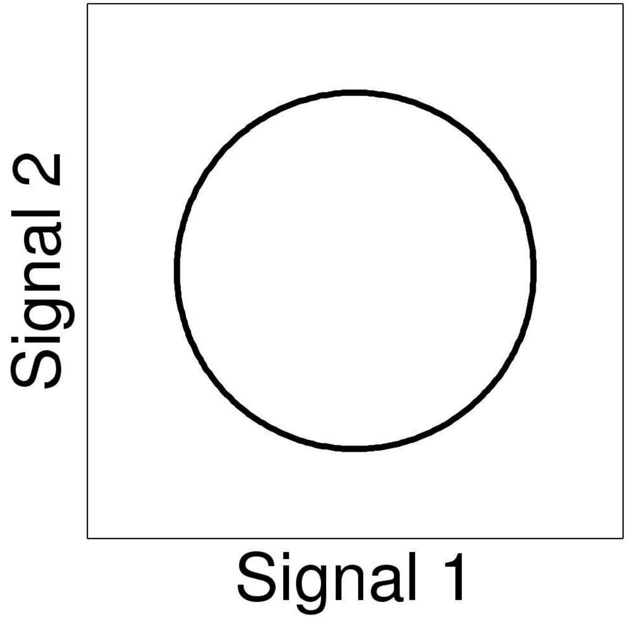
Smaller hard to characterize
Larger hard to build

The need for quadrature

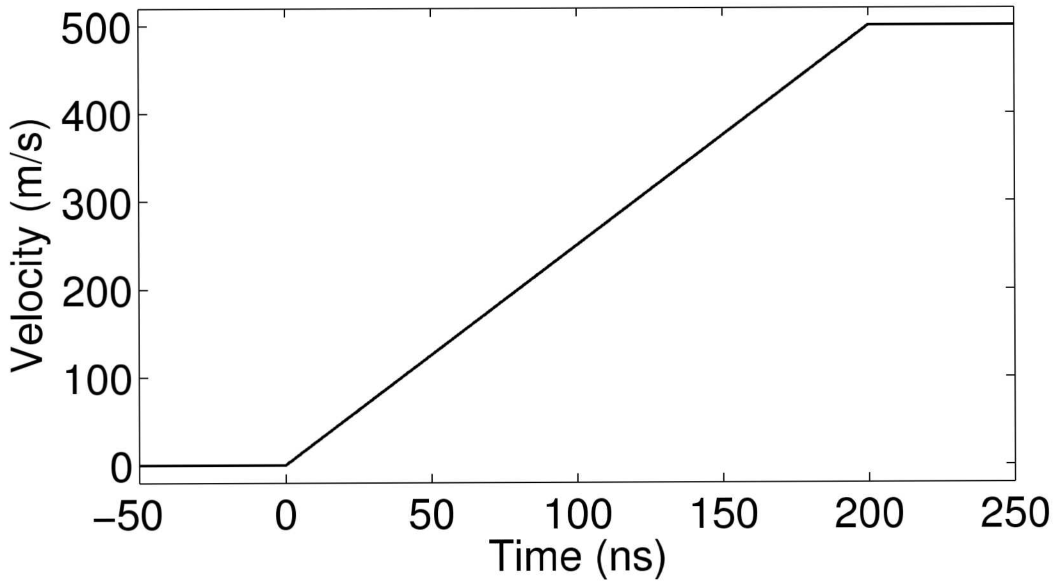
Inverting a sinusoid is not always easy
- Arcsine and arccosine defined over 180 degrees
- Steep sections are sensitive
- Peaks/troughs are insensitive

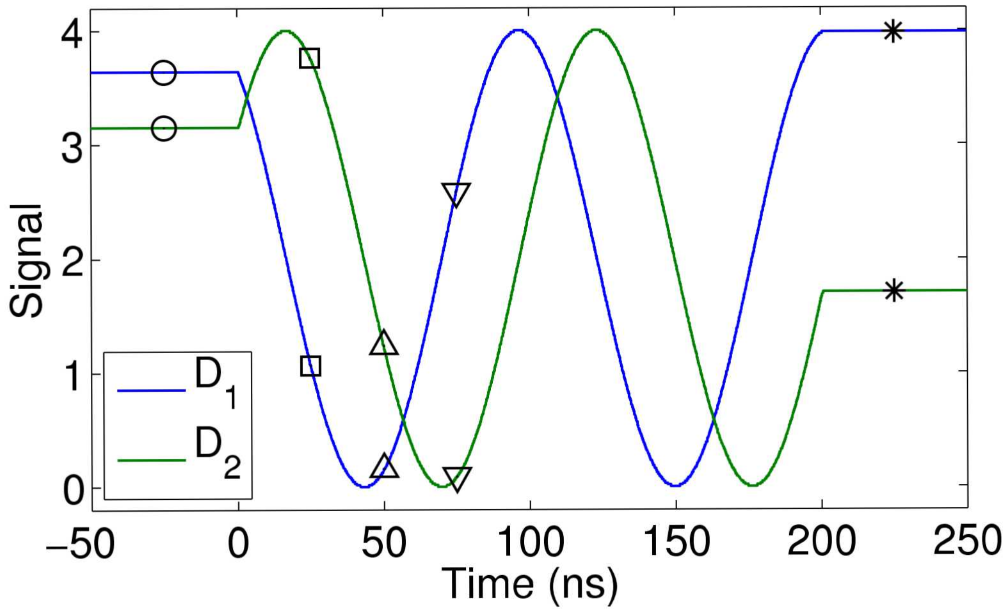
Measuring 2+ quadrature signals provides:
- A robust inversion
- Reduces the effect of amplitude variations
- Arctangent defined over 360 degrees



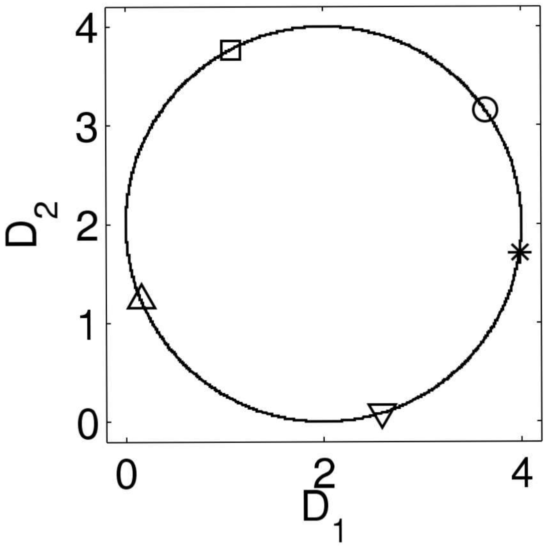


Ramp example (1 ns delay)



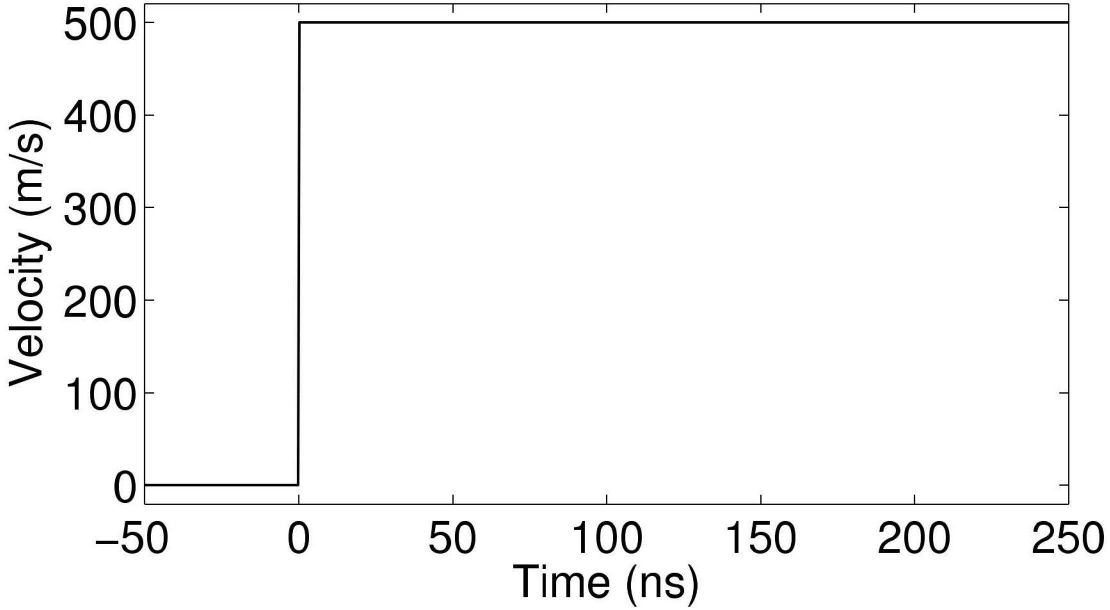


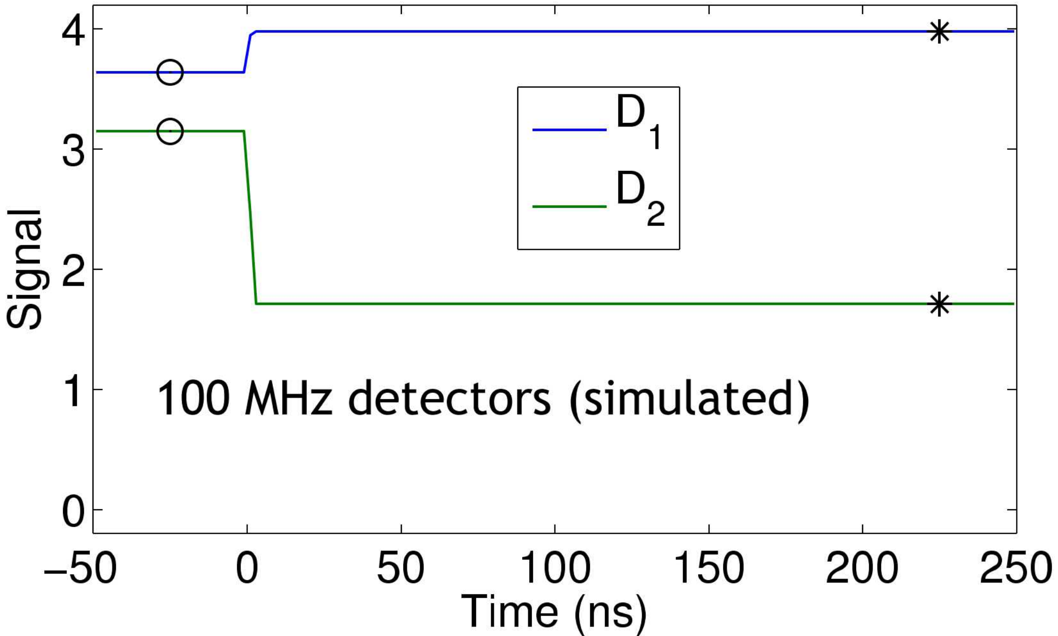
Quadrature resolves fringe wrapping



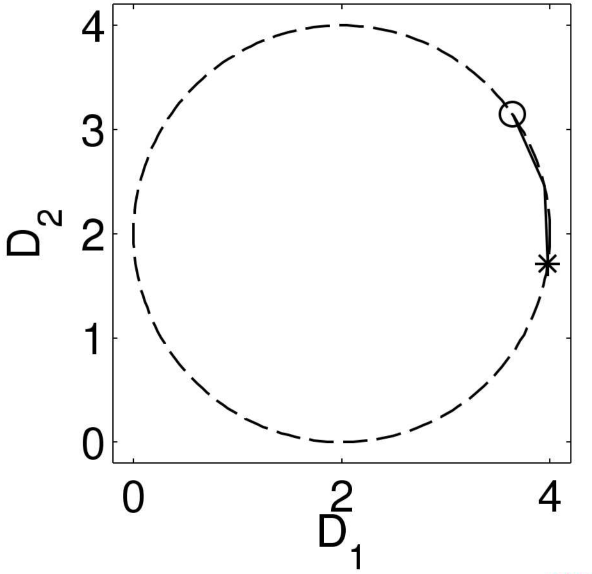
Signals change when velocity changes

Shock example (1 ns delay)





Motion is backwards?



Signals change over etalon delay

Cold, hard realities of VISAR

Fringe shift only known to an integer offset

- Detectors that cannot keep up with optical signal may "lose/jump fringes"
- Multiple VPFs are generally used to resolve this ambiguity
- VISAR is designed to measure fringe shift from a **single** Doppler shift
  - Multiple velocities cause confusing interference
  - VISAR ellipse collapses to its center

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

$$u = K_1(F_1 + N_1)$$
$$= K_2(F_2 + N_2)$$

Ellipse position/size changes with light level!

VISAR evolution

Push-pull quadrature [Hemsing, Rev. Sci. Instrum. **50**, 73 (1979).]

- Four signal phases (0, 90, 180, and 270 degrees)
- Explicitly removes coherent/incoherent light variation

Fiber coupling

- VISAR was originally an open-beam diagnostic
- Open beam now used primarily for line VISAR measurements

Faster detectors

- Optical streak-cameras (ORVIS)
- Improved photodiodes/photodetectors
- Faster digitizers

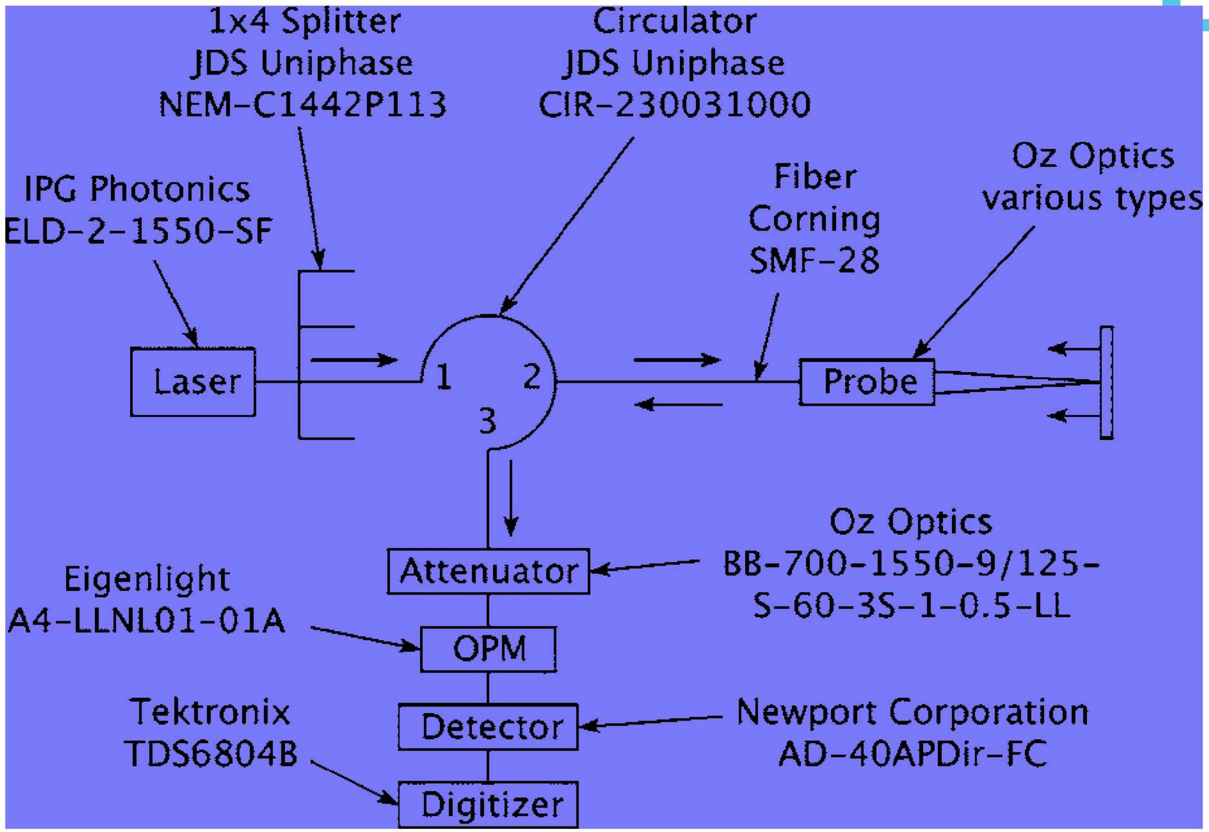
Incremental changes over the past two decades

Photonic Doppler Velocimetry (PDV)

PDV born at LLNL (2002-2003)

Utilizes advances from the telecommunications industry (1550 nm)

- Compact fiber lasers
  - 9 um core diameter (SMF)
  - Narrow line width (<10-100 kHz)
- Three-port circulator (magic!)
  - Port 1 input goes to port 2
  - Port 2 input goes to port 3
- High speed detectors/digitizers (>10 GHz)



Strand et al, Rev. Sci. Instrum. 77, 83108 (2006).
Reference light comes from probe's back reflection

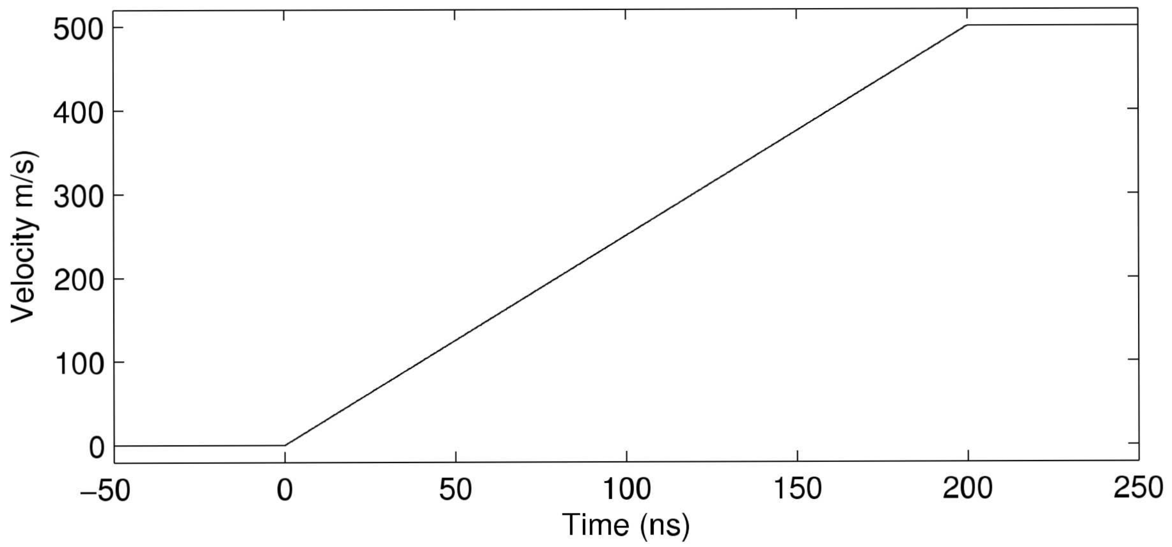
See Dolan RSI **91**, 051501 (2020) for comprehensive review

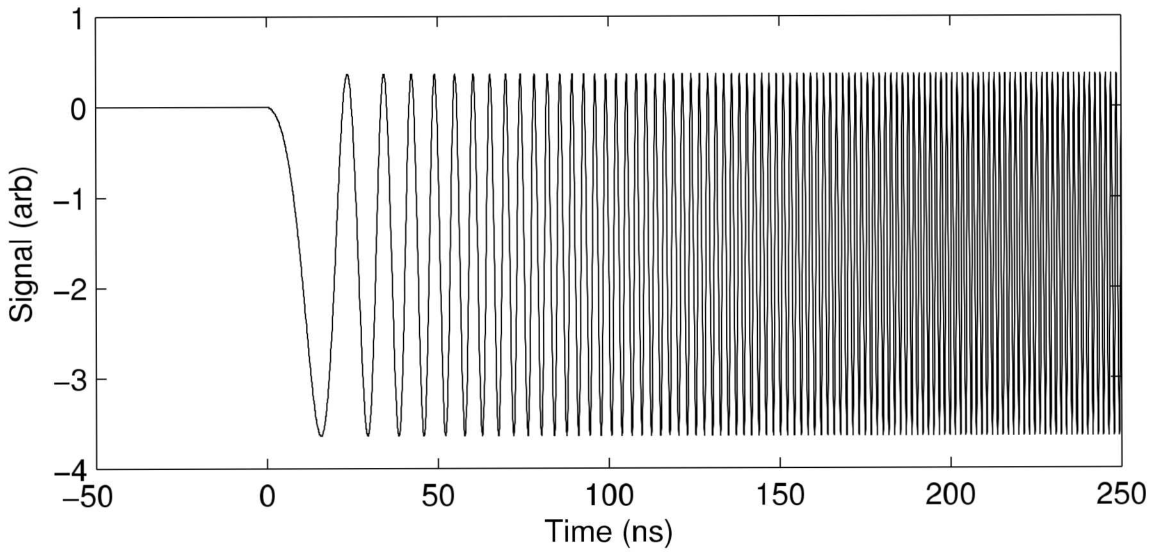
Example: ramp measurement with PDV

Michelson interferometer
- 775 nm motion= 1 fringe

Signal frequency changes with velocity
- Displacement interferometer lives again (in fiber)!

$$\frac{dF}{dt} = B(t) = \frac{2v}{\lambda_0}$$

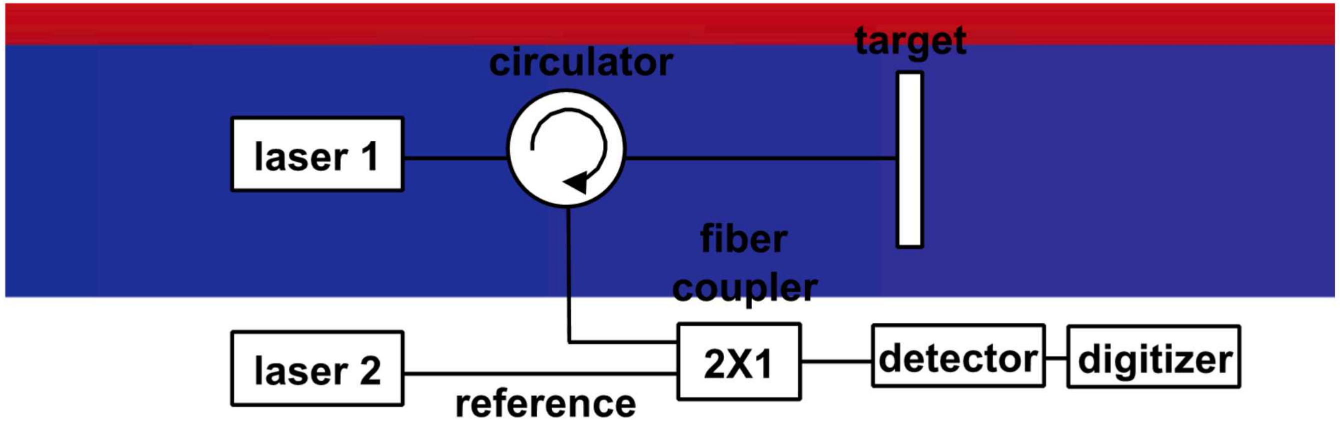




There are many names for and configurations of PDV

Conventional PDV

- One laser wavelength
- Confusingly called heterodyne velocimetry (HetV)

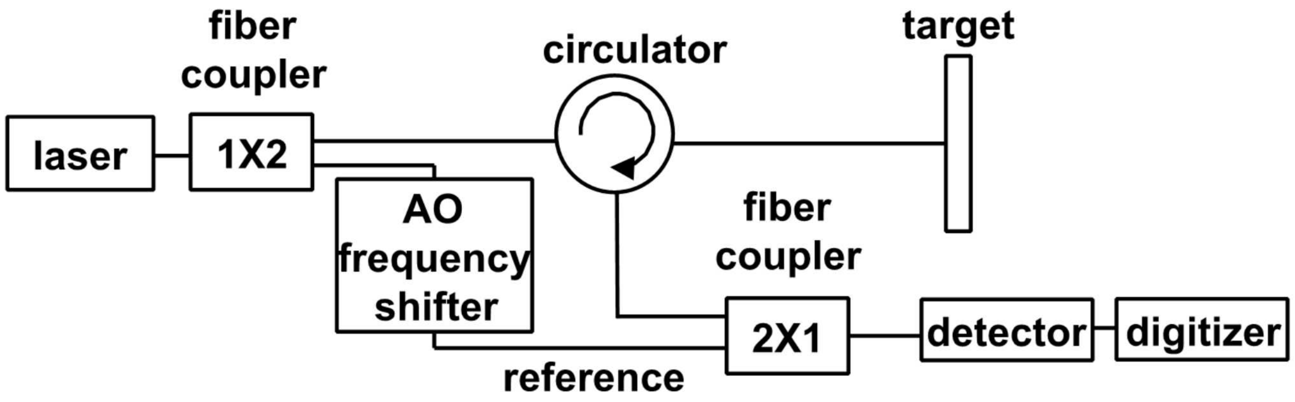


Quadrature PDV

- Phase-based measurement (3 signals)
- Triature, PDI, DISAR, …

Frequency-shifted PDV

- Two laser wavelengths OR laser + shifter

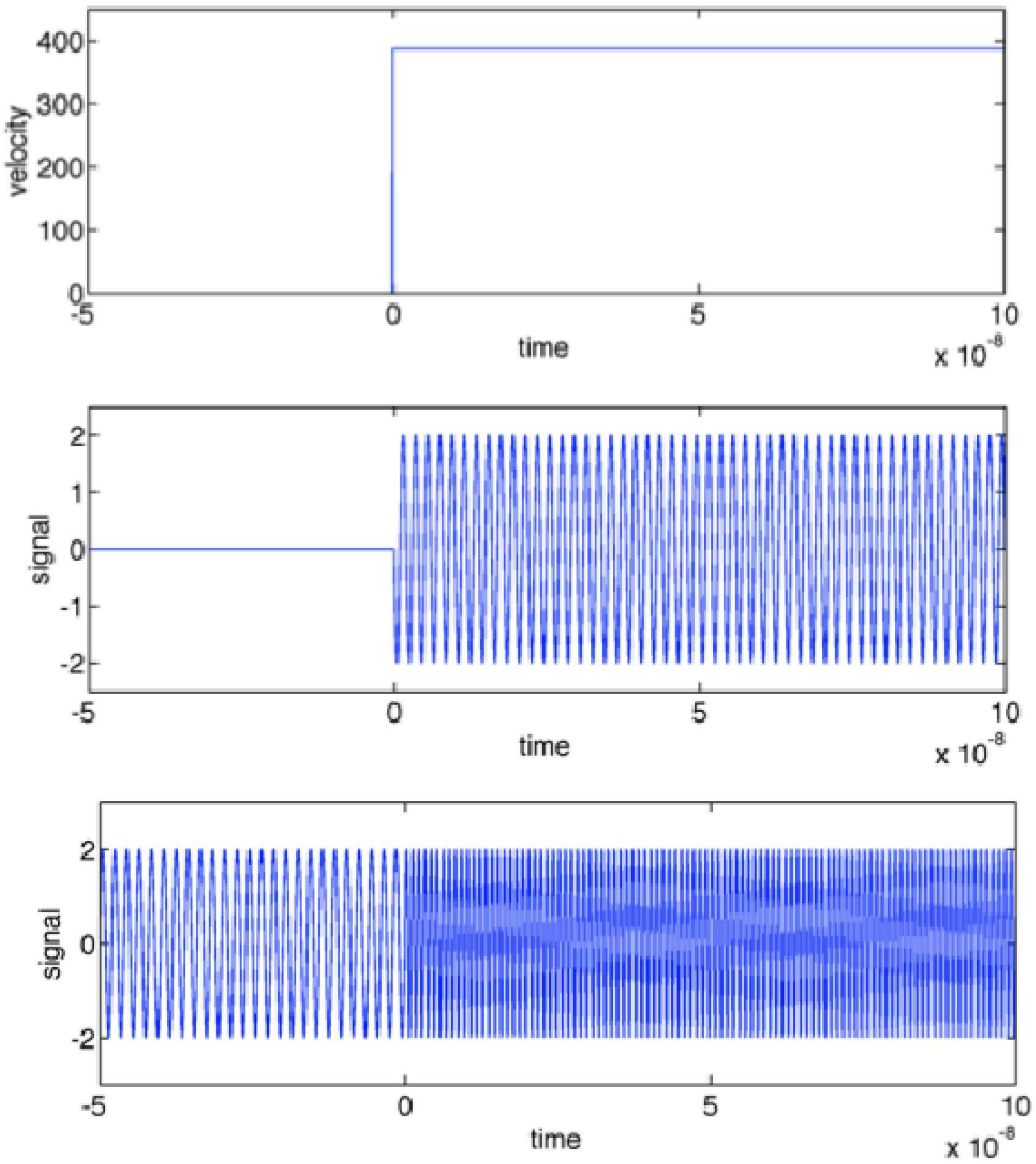


D. Dolan, "Accuracy and precision in photonic Doppler velocimetry," Review of Scientific Instruments **81**, 53905 (2010).

Example: step measurement with PDV

Conventional PDV
- No motion, no fringes

Frequency-shifted PDV
- Always fringing, even at rest
- Helpful in digitizer setup



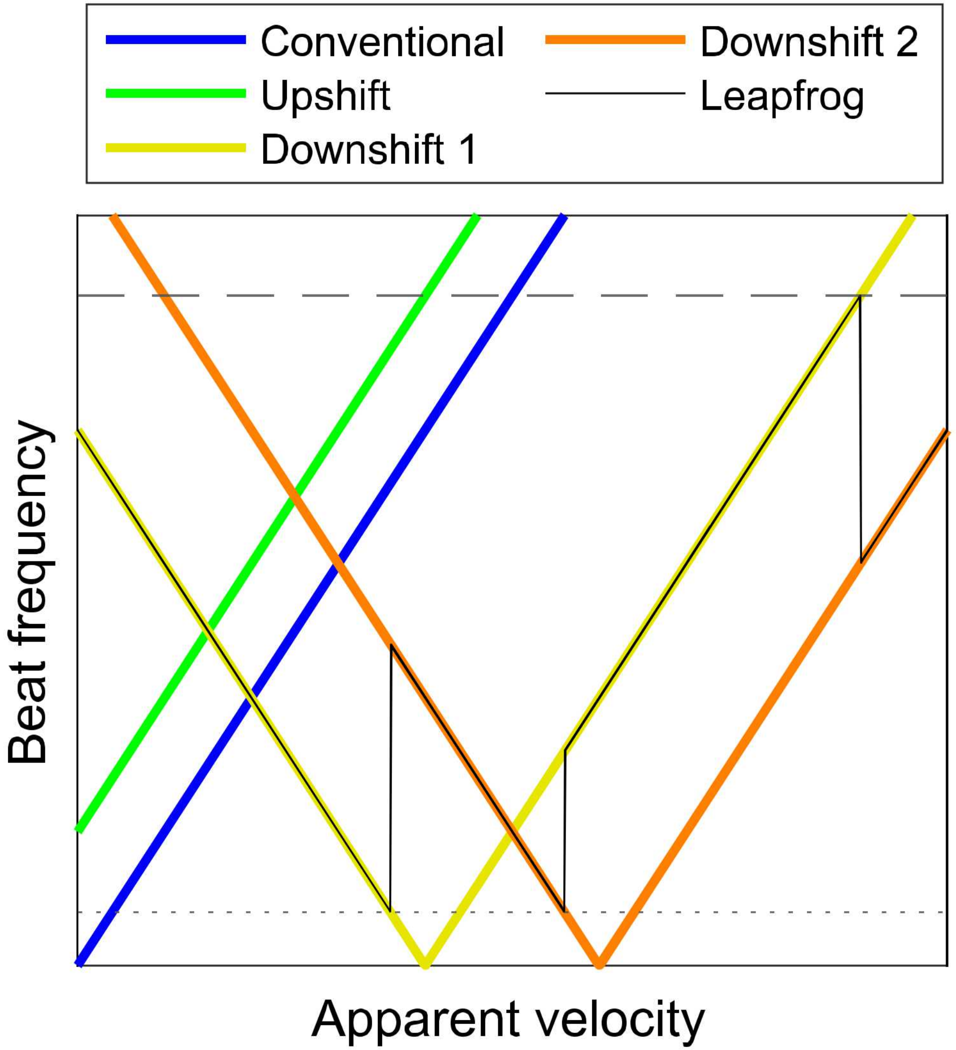
Mapping velocity to beat frequency

Frequency shifting moves mapping up/down

- This is done by tuning laser wavelengths
- Upshift: reference longer than target
- Downshift: reference shorter than target

Mapping is not unique

- Each beat frequency is associated with two velocities
- Physical constraints can eliminate one choice
- "Leapfrog" measurements use multiple references to resolve this ambiguity



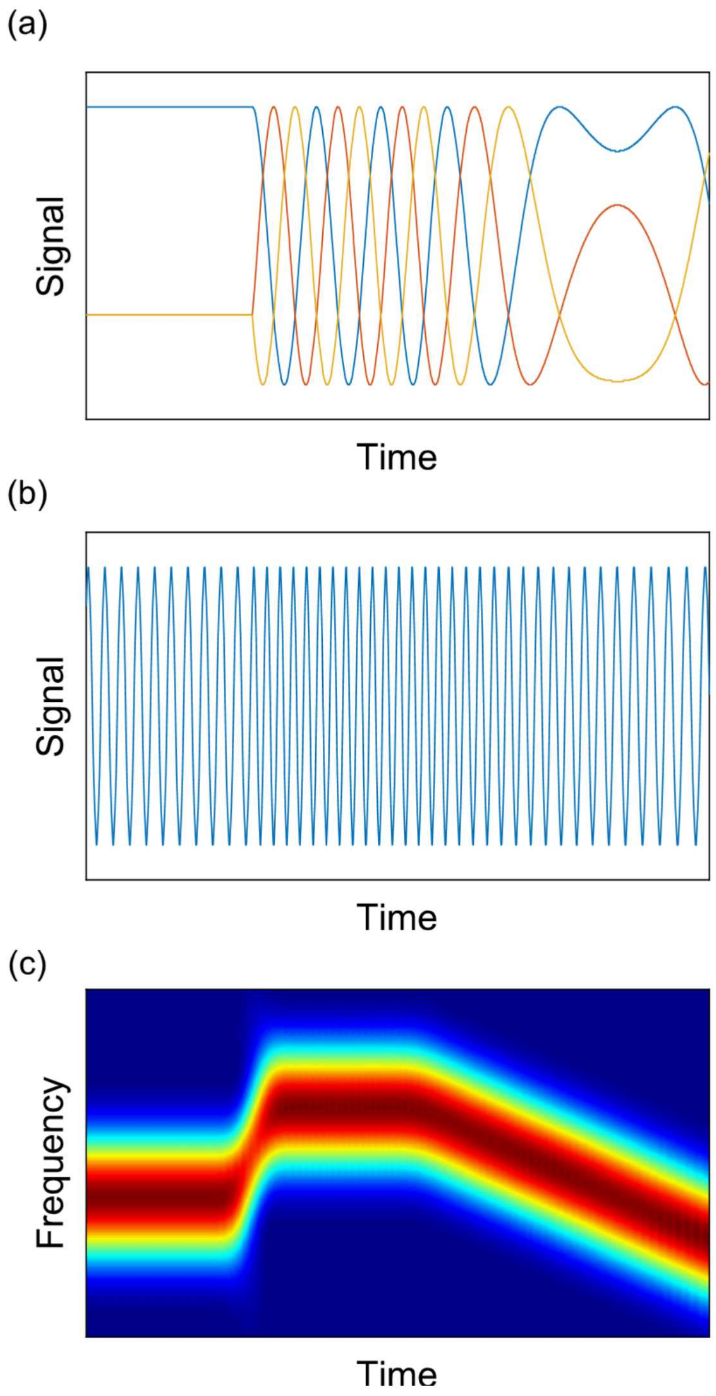
$$B = \left| \nu_T - \nu_R + \frac{2}{\lambda_T} v^* \right|.$$

A more complicated example

(a) Quadrature PDV signals
- 120 degree phase shifts
- Frequency is time-derivative of phase shift

(b) Frequency-shifted signal
- Same content as (a)
- Difficult to interpret by eye

(c) Time-frequency representation of (b)
- History is obvious in the spectrogram



The 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).

Generating a PDV spectrogram

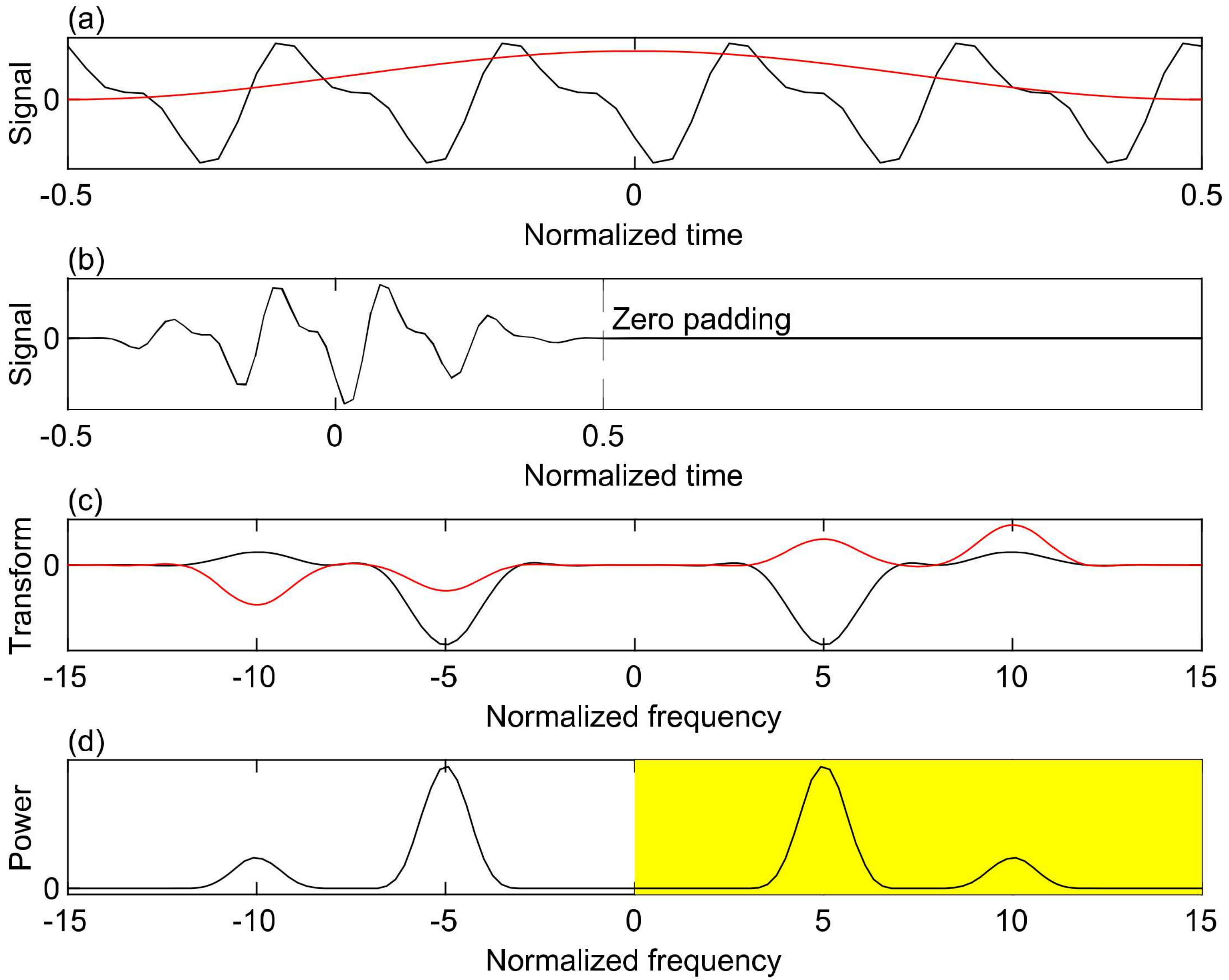
(a) Extract local region

(b) Multiple local region by window function and zero pad to a power of two.

(c) Use FFT to determine complex spectrum

(d) Calculate the power spectrum for positive frequencies only

Every slice of the spectrogram is built from steps (a)-(d).

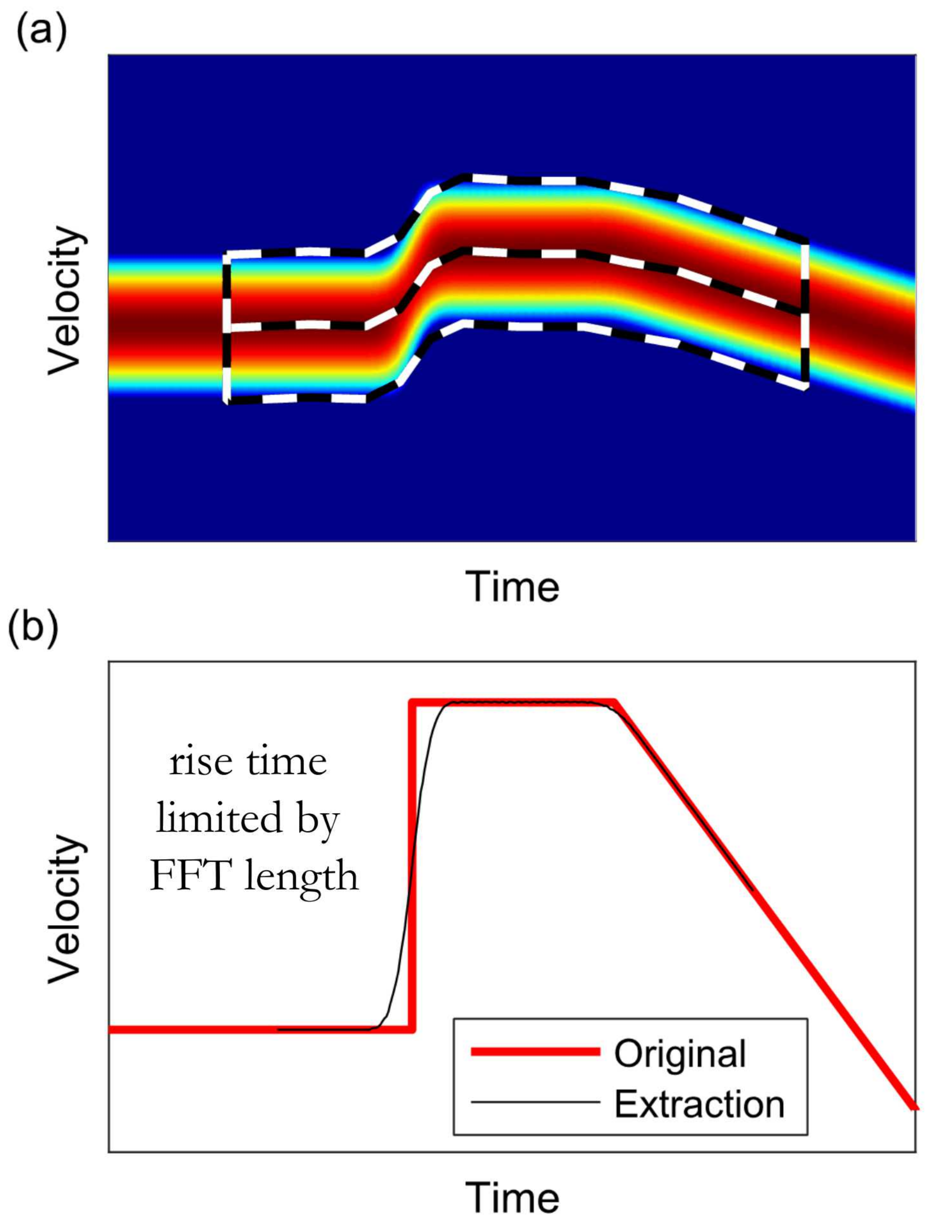


Extracting the velocity history

Region of interest (ROI) selection
- Usually needs human attention

Determine peak location at each time step, subject to ROI
- Centroid, peak fit, etc.
- Subtract reference frequency (as needed)
- Scale by half wavelength

"Spectrograms don't lie, but histories sometimes do", -David Holtkamp

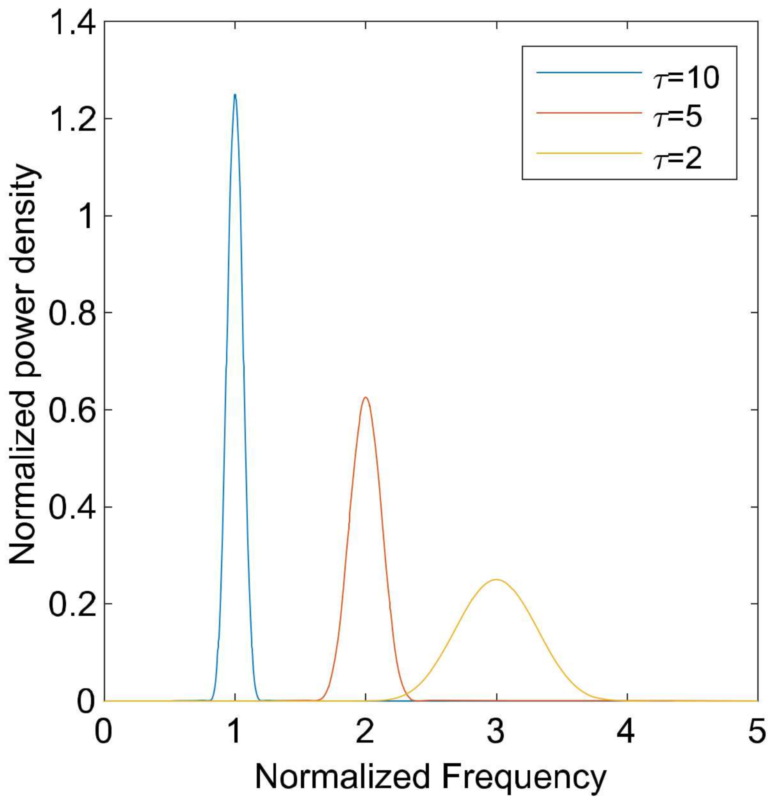


Time resolution versus frequency uncertainty

Standard uncertainty principle applies but is misleading
- Time/frequency width product is fixed

Peak locations can be determined more accurately than one width
- Frequency resolution scales with duration to the -3/2 power

Similar limits apply to VISAR
- Etalon delay sets the limiting time scale
- PDV time scale defined in software



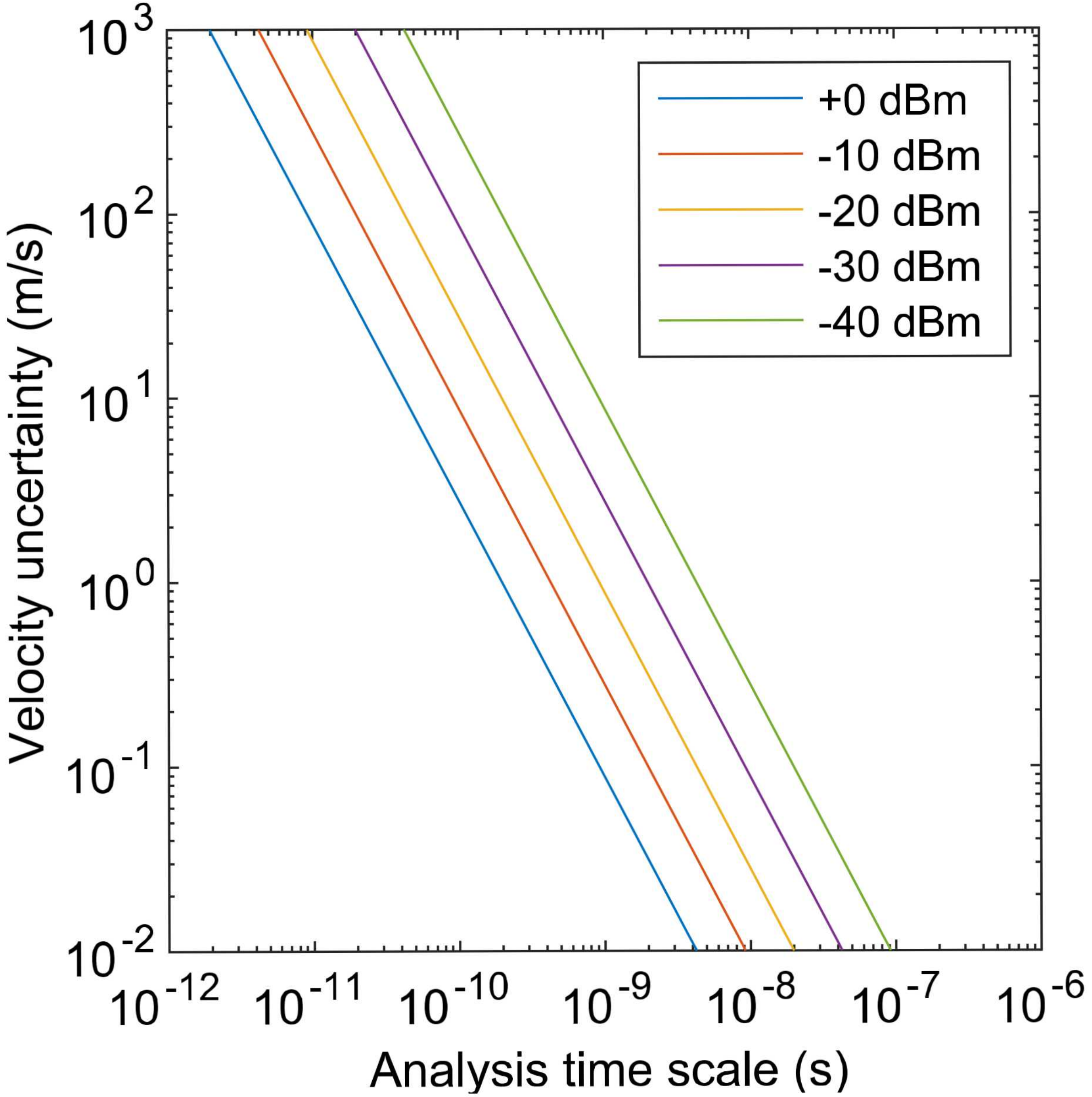
$$\sigma_B = \sqrt{\frac{6}{f_s \tau^3}} \frac{\sigma_s}{A} \frac{1}{\pi}.$$

Limiting resolution in PDV

Performance determined by light return
- Usually specified on a log scale
- 0 dBm is 1 mW, -10 dBm is 0.1 mW
- +20 dBm typically sent to probe
- 30 to 60 dB probe return (efficiency)

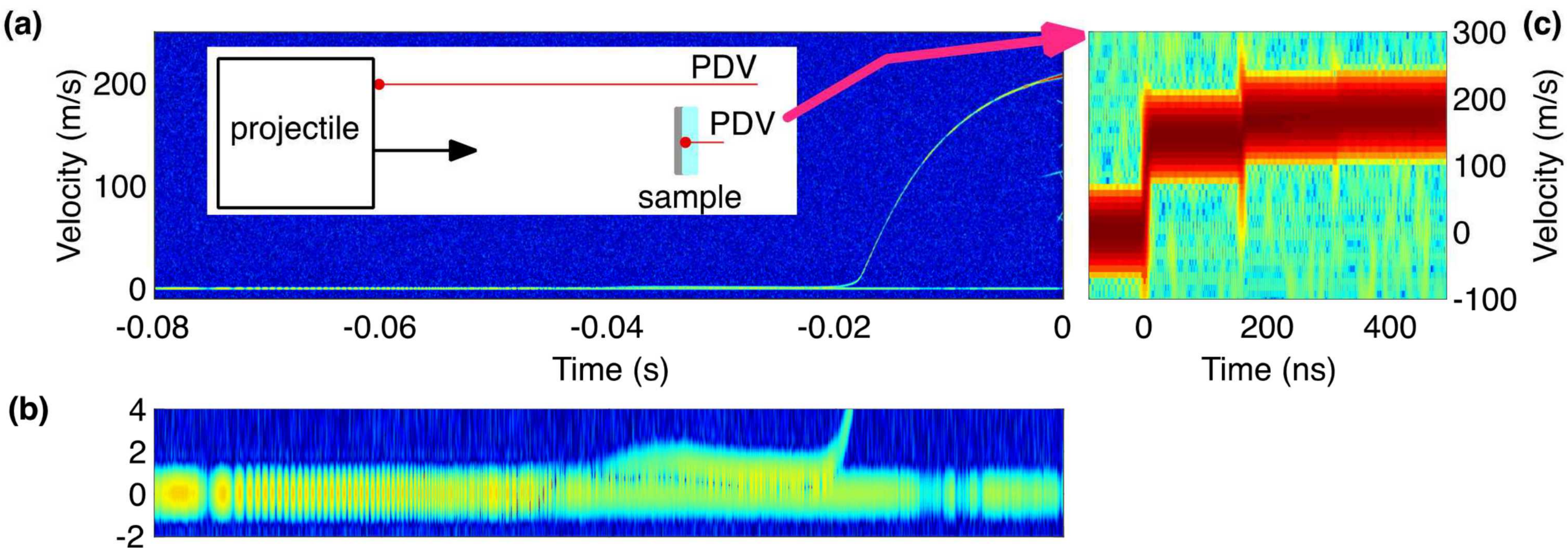
Time scale plays a significant role
- m/s uncertainty plausible at 1 ns
- Sub m/s uncertainty trivial >100 ns

This assumes well-separated spectra!



PDV examples

Impact experiments



(a) Spectrogram for projectile launch in a wrap-around gas gun

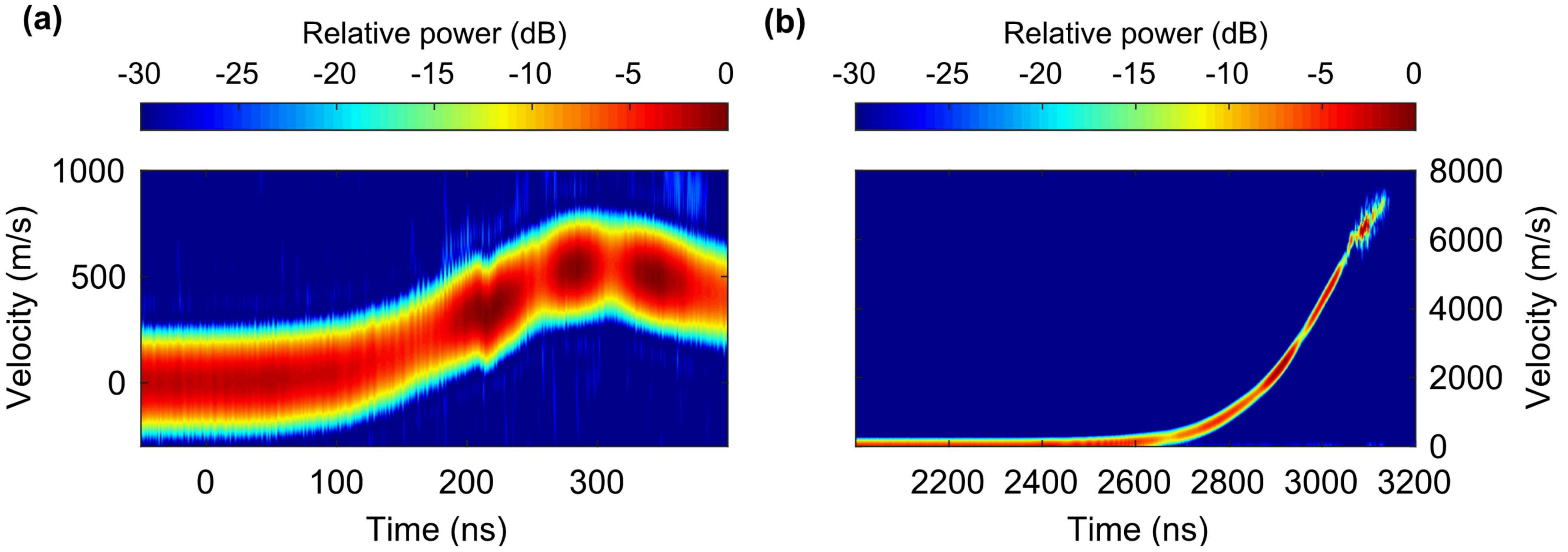
(b) Early details show the projectile creeping through the breech before takeoff

(c) Reverberating shock measurement of the sample during impact

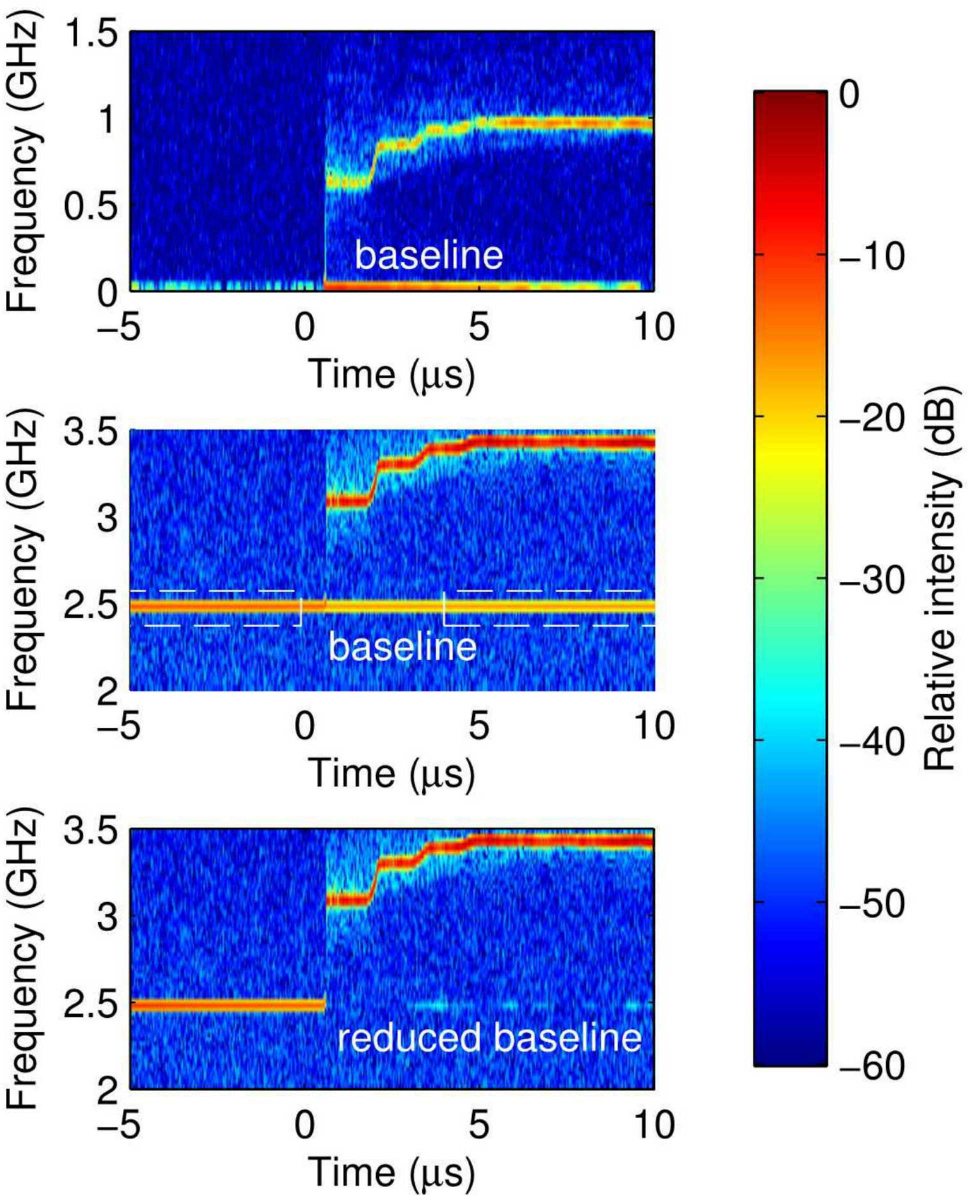
Ramp wave measurements

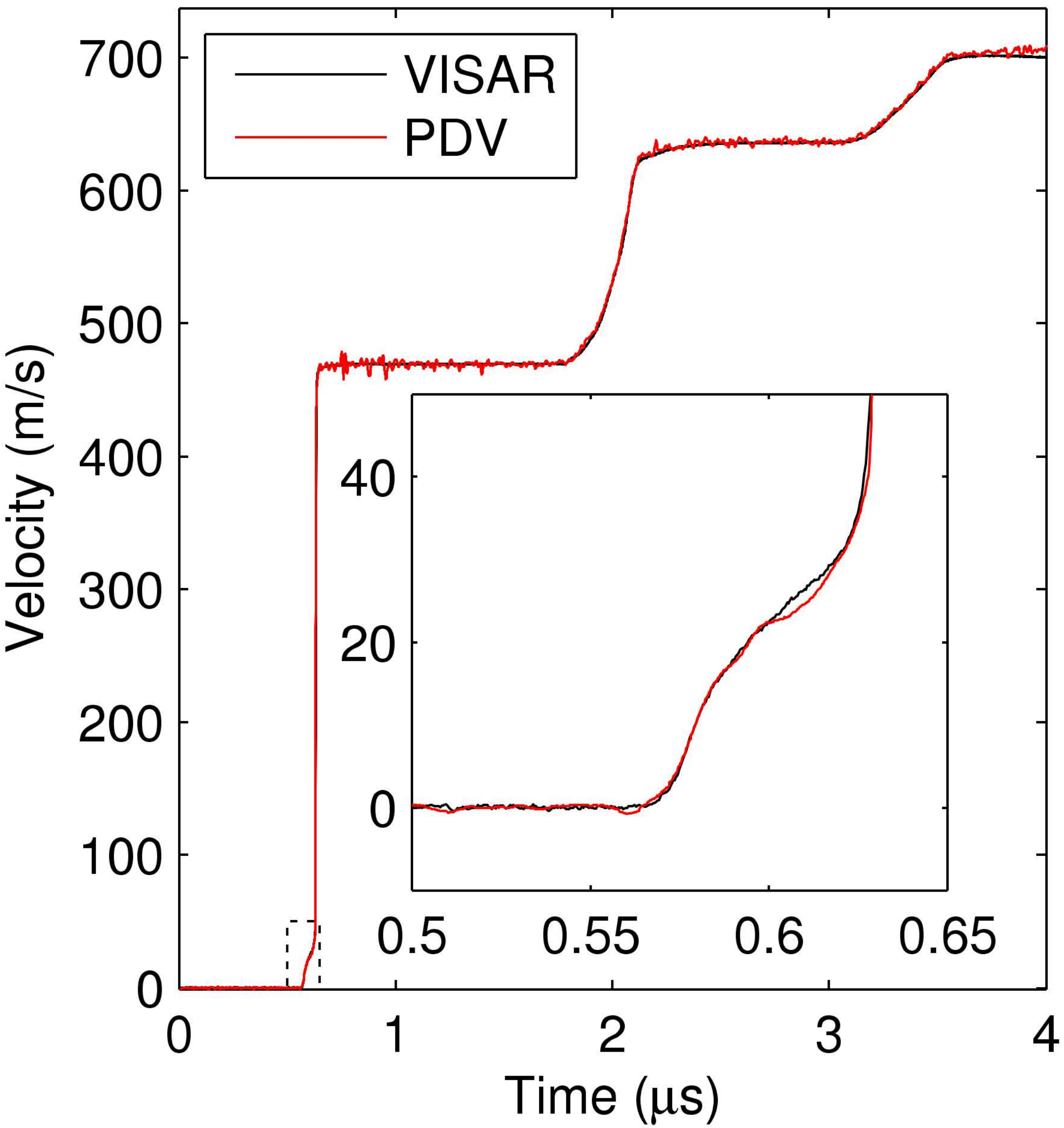
Ramp compression of a water sample

Implosion of a copper cylinder



Velocity history example





VISAR versus PDV

Differences between VISAR and PDV

VISAR

- Open beam or multi-mode fiber
- Usually visible light (532 nm)
- Max. velocity independent of bandwidth
- Time scale defined in hardware
- Usually analyzed in the time domain
- Optimized for single-velocity measurements

PDV

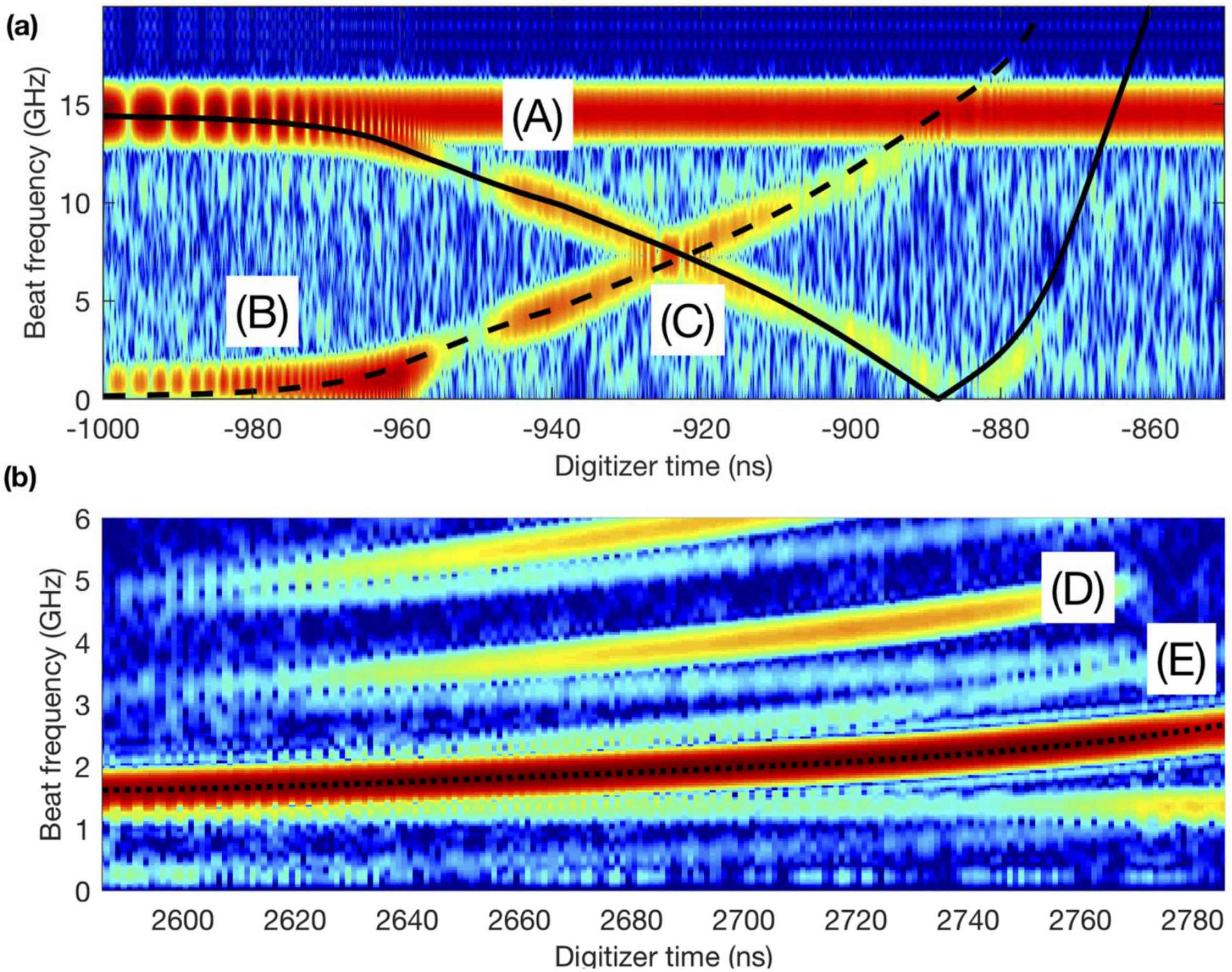
- Single-mode fiber
- Usually infrared (1530-1565 nm)
- Max. velocity depends on bandwidth
- Time scale defined in software
- Usually analyzed in the frequency domain
- Can measure multiple simultaneous velocities

PDV analysis can be tricky

(a) Measurement with extended baseline (A), conventional artifact (B), and the down-shifted beat of interest (C).

(b) Measurement with electrical (D) and optical (E) harmonics.

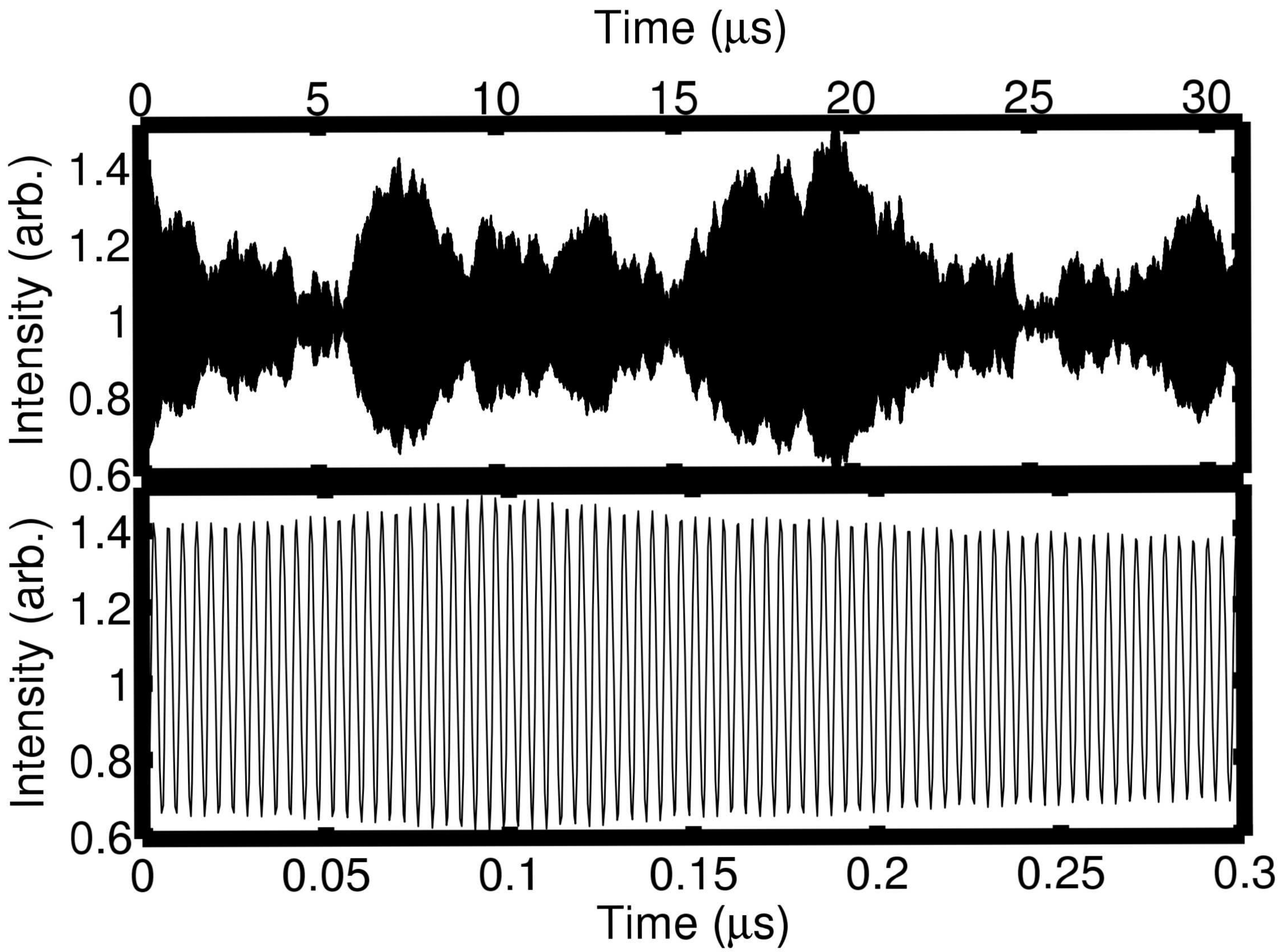
Overlapping features create spectrogram modulations



Other PDV challenges

Dynamic speckle
- Highly coherent lasers + rough reflectors
- Random dropouts
- Can be mitigated with redundant probes

Fiber limitations
- 9 um core limits max power
- Stimulated Brillioun scattering limits power over long lengths



So which is better?

VISAR is technically more sensitive but also more complicated

- Shorter wavelength and multiple signals (reduces noise)
- Open beam alignments and multiple signals (more digitizer channels)

…but both VISAR and PDV have their merits

- Use what you have for wave profiles (windowed samples, 1D compression)
- Use PDV for everything else (detonation studies, ejecta measurements,…)

In a new facility, VISAR may not make sense for velocities under 15 km/s

- Digitizer dominates the upfront cost of PDV (can easily exceed $100,000)
- PDV operation/maintenance are generally much easier than VISAR

Summary and exercises

Summary

Velocimetry is a core diagnostic for dynamic compression research

- Virtually every experiment will have VISAR and/or PDV
- Directly tied to the jump conditions and wave simulations
- Historical data based on arrival time measurements

Optical velocimetry now usually based on the Doppler shift

- VISAR encodes that shift as phase on a set of quadrature signals
  - Requires 3-4 measurements, but not high bandwidth
  - Does not tolerate more than one velocity at a time
- PDV encodes that shift as beat frequency change (only 1 signal needed)
  - Only 1 measurement needed, possibly high bandwidth
  - Can handle multiple velocities, though overlapping features are hard to analyze

Exercise 1

Suppose that you have a 1550 nm PDV and need to measure a projectile moving at 1000 m/s. What is the minimum recording bandwidth needed to track this motion?

For same velocity, what is the etalon delay needed for ten fringes in a 532 nm VISAR?

Bonus question: what is the limiting velocity resolution for the above PDV measurement assuming 10% signal noise, 80 GS/s sampling, and 10 ns FFTs? How does this compare to VISAR? Hint: Barker's rule of thumb is 1-2% of the fringe constant.

Exercise II

Suppose a wedged projectile moves horizontally at velocity v.

- What velocity would a VISAR at location A measure? What about a PDV at location A?
- Optical measurements at location B see different parts of the projectile at it moves by; the illuminated spot gets closer. What velocity would VISAR/PDV measure at this location?
- Does the distinction that VISAR is a "velocity" interferometer and PDV is a "displacement" interferometer play any role here?