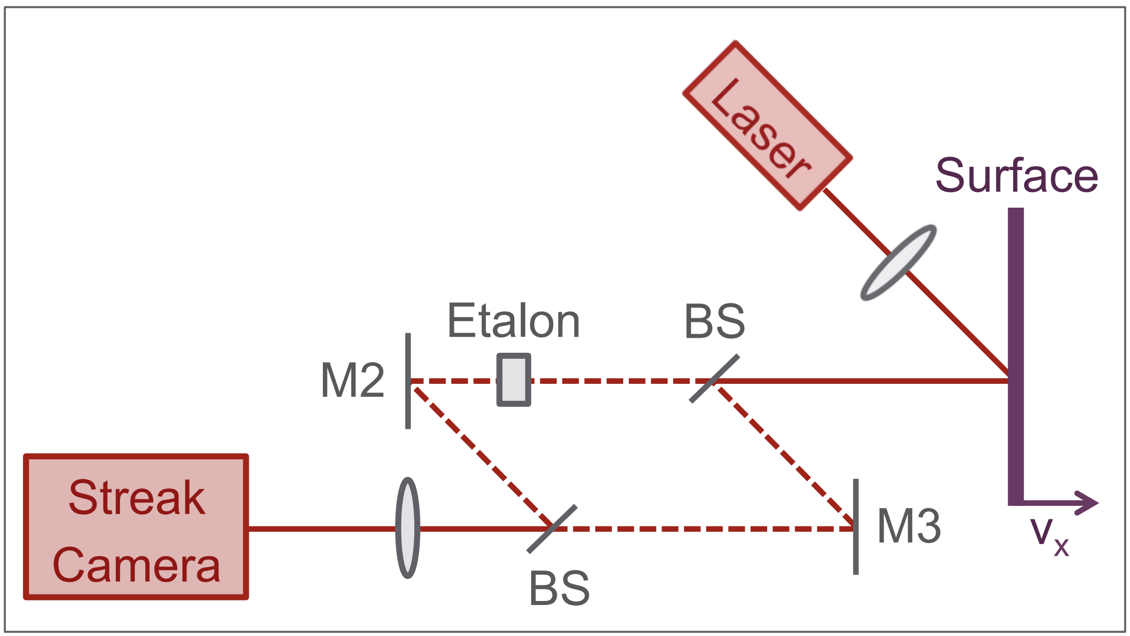
Velocity Interferometer System for Any Reflector (VISAR)

Foundational Physics and Applications

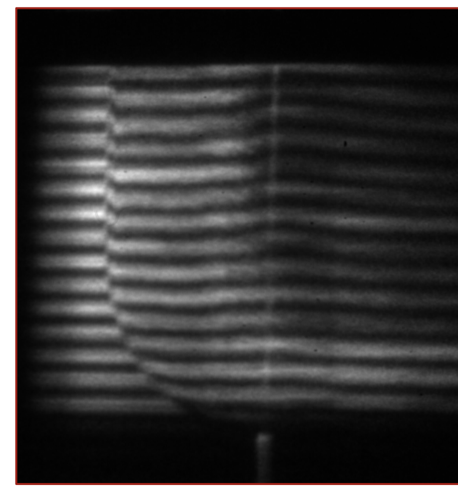
What is VISAR?

Velocity **I**nterferometer **S**ystem for **A**ny **R**eflector

- Measures change in Doppler shift of light reflected off a moving surface
- Used to calculate velocity of surface



VISAR Setup Diagram

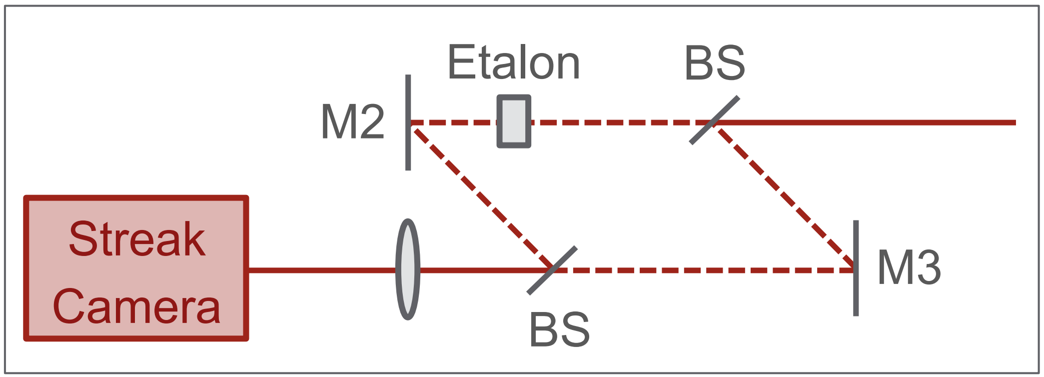


Fringe Pattern
Smith (J. Appl. Phys. 2013)

Interferometry Principles

Superposition of two beams

- Calculate Doppler shift by analyzing interferometer fringes
- Desired: fringe phase



Interferometer Setup

$$I^2 = |E| = E \cdot E^*$$

$$I^2 = [E_1 + E_2][E_1^* + E_2^*]$$

$$I^2 = |E_1^2| + |E_1^2| + 2E_1E_2\cos\theta$$

$$I^2 = I_1 + I_2 + 2E_1E_2\cos\theta$$

Interference term

- Express as sample function

$$f(x,t) = b(x,t) + a(x,t)\cos[\phi(x,t) + 2\pi f_0 x + \delta_0]$$

$$I^2 = I_1 + I_2 + 2E_1E_2\cos\theta$$

$\phi(x,t)$ fringe phase

$2\pi f_0 x$ phase ramp

δ_0 initial phase

Interferometry Principles

Fourier method to resolve fringe phase

- Base equations

$$f(x,t) = b(x,t) + a(x,t)\cos[\phi(x,t) + 2\pi f_0 x + \delta_0]$$

- Convert functional forms

$$f(x,t) = b(x,t) + c(x,t)e^{i2\pi f_0 x} + c^*(x,t)e^{-i2\pi f_0 x}$$

where

$$c(x,t) = \frac{1}{2}a(x,t)e^{i\delta_0}e^{i\phi(x,t)}$$

- FFT

$$F(f,t) = B(f,t) + \int_{-\infty}^{\infty} c(x,t)e^{i2\pi f_0 x}e^{-ifx}dx + \int_{-\infty}^{\infty} c^*(x,t)e^{-i2\pi f_0 x}e^{-ifx}dx$$

$$F(f,t) = B(f,t) + \int_{-\infty}^{\infty} c(x,t)e^{i2\pi(f_0 - f)x}dx + \int_{-\infty}^{\infty} c^*(x,t)e^{-i2\pi(f_0 + f)x}dx$$

$$F(f,t) = B(f,t) + \underline{C(f - f_0,t)} + \underline{C(f + f_0,t)}$$

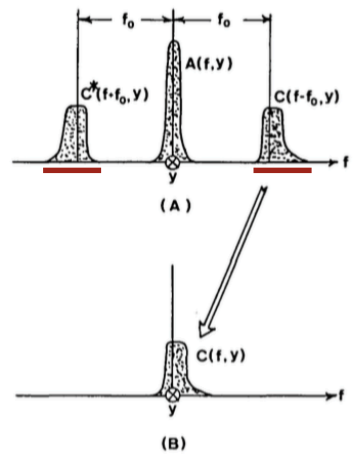


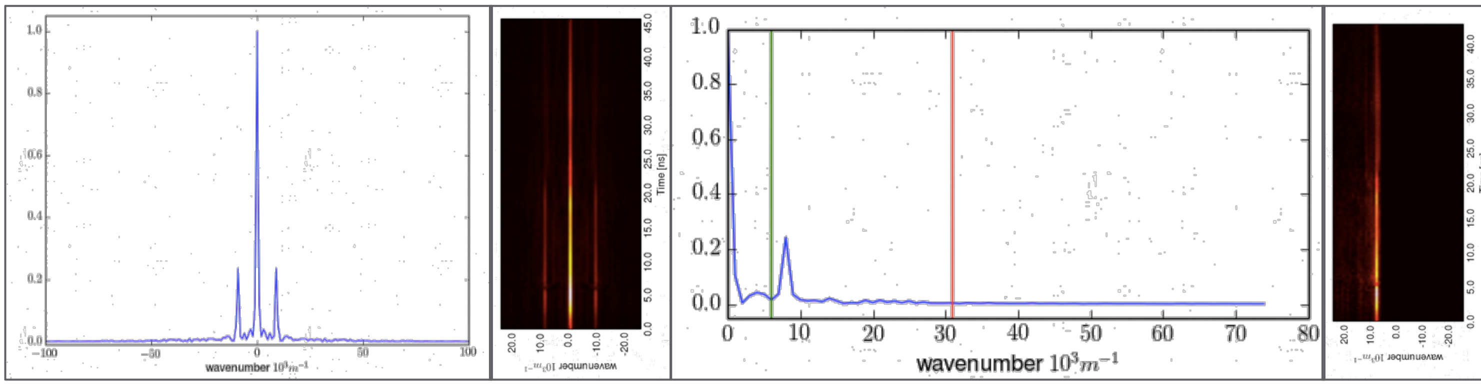
Fig. 1. (A) Separated Fourier spectra of a noncontour type of fringe pattern; (B) single spectrum selected and translated to the origin. The y axis is normal to the figure.

Theoretical signal selection
Takeda (J. Opt. Soc. Am. 1982)

Interferometry Principles

Signal Isolation

$$F(f,t) = B(f,t) + \underline{C(f - f_0, t)} + C^*(f + f_0, t)$$



Signal filtering for single-shift term; Smith (J. Appl. Phys. 2013)

- Inverse FFT

$$c(x,t) = \frac{1}{2} a(x,t) e^{i\delta_0} e^{i\phi(x,t)}$$

$$f(x,t) = \int_{-\infty}^{\infty} C(f - f_0) e^{ixf}$$

Euler's formula

$$f(x,t) = \int_{-\infty}^{\infty} C(f - f_0)\left[\cos(xf) + i\sin(xf) df\right]$$

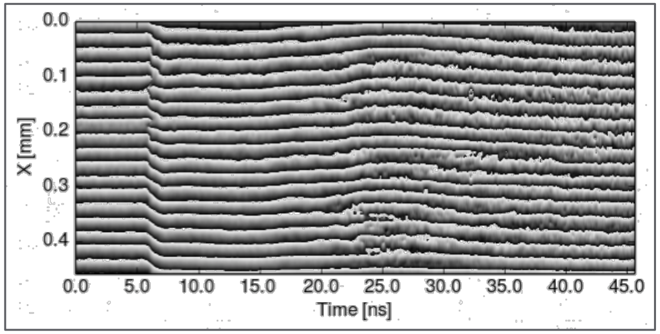
Used to solve for wrapped phase

Interferometry Principles

Phase Extraction

- Wrapped phase

$$\mathrm{Re}\left[f(x,t)\right] \propto \sin(\phi(x,t) + 2\pi f_0 x + \delta_0)$$
$$\mathrm{Im}\left[f(x,t)\right] \propto \cos(\phi(x,t) + 2\pi f_0 x + \delta_0)$$

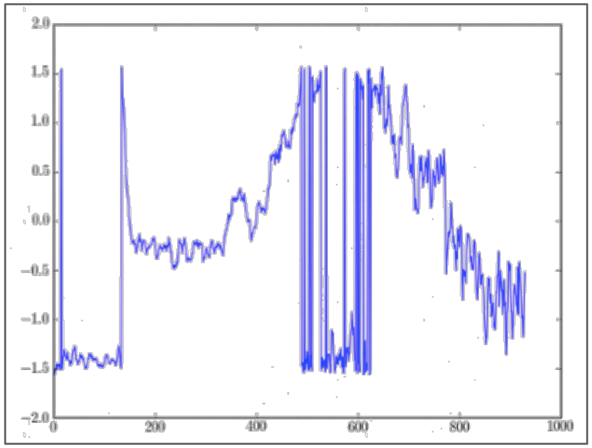


Wrapped phase map
Smith (J. Appl. Phys. 2013)

$$P(\phi(x,t) + 2\pi f_0 x + \delta_0) = \arctan\left(\frac{\mathrm{Re}\left[f(x,t)\right]}{\mathrm{Im}\left[f(x,t)\right]}\right)$$

Discontinuity Resolution

- Occurs as arctan() goes through full rotations



Phase time evolution at single x
Smith (J. Appl. Phys. 2013)

- Also observe “fringe-hopping” (algorithm misidentifies fringe shifts)

Velocity Calculation

Velocity proportional to fringe phase

- Once phase determined, use VPF (velocity per fringe) to calculate velocity

  - Normalized phase difference

$$F(x,t) = \frac{\phi(x,t) - \phi(x,t_i)}{2\pi}$$

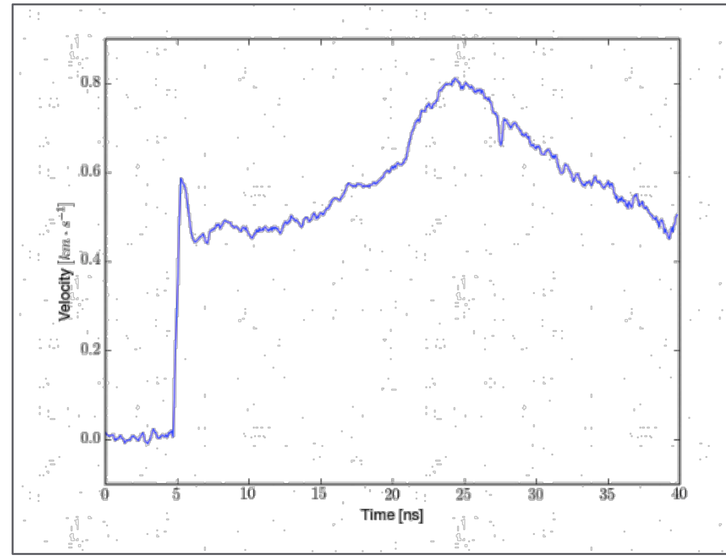
  - Velocity (VISAR approximation)

$$v(t - \tau_0) = v_i + \kappa F(x,t) + O(\tau_0)$$

  - Constant VPF

$$\kappa = \frac{\lambda_o}{2\tau_0(1+\delta)}$$

λ_0	wavelength
τ_0	etalon time delay
$(1+\delta)$	etalon dispersion correction

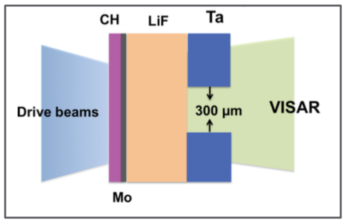


Velocity time evolution at single x
Smith (J. Appl. Phys. 2013)

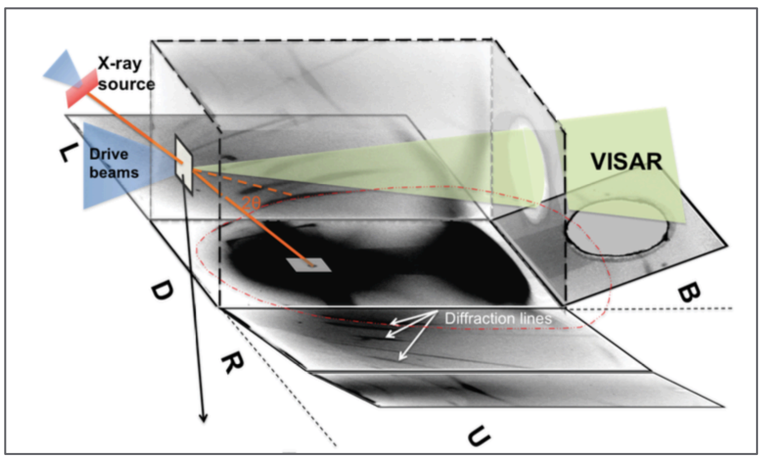
Example: Shock Physics

VISAR measures shock “breakout time”

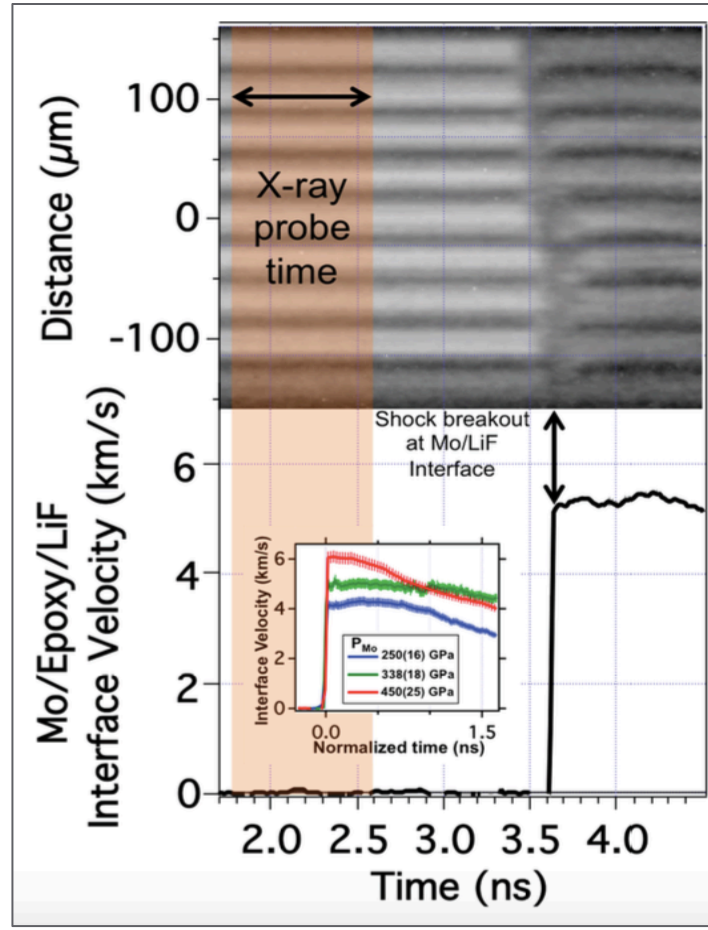
- Elastic/Plastic shockwaves
- Plasma expansion



Target configuration
Wang (Phys. Rev. B, 174114 (2015)



Experimental setup for shock compression
Wang (Phys. Rev. B, 174114 (2015)



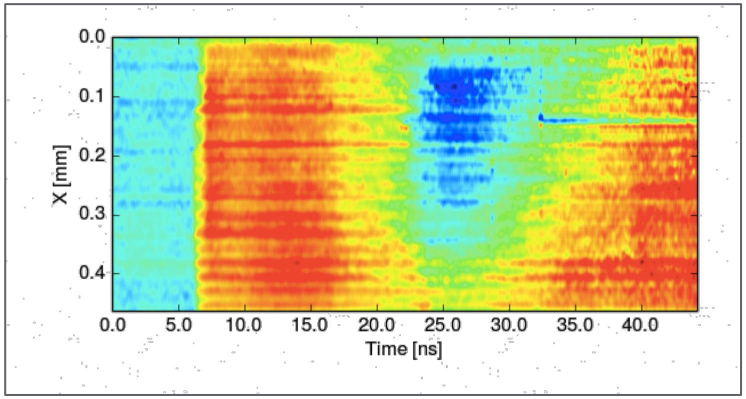
VISAR and velocity of shock breakout
Wang (Phys. Rev. B, 174114 (2015)

VISAR Limitations

Amplitude-sensitive system

Sources of error

- Beam
  - Spatially-varying beam
  - Optical component alignment and back reflections
- Camera
  - Camera thermal noise + background pattern
  - Distortion “Speckle pattern”
- Target
  - Surface roughness -> non-uniform reflectivity



Velocity time evolution at all x locations
Smith (J. Appl. Phys. 2013)

Summary

Velocity **I**nterferometer **S**ystem for **A**ny **R**eflector

- Measures change in Doppler shift of light reflected off a moving surface
- Used to calculate velocity of surface

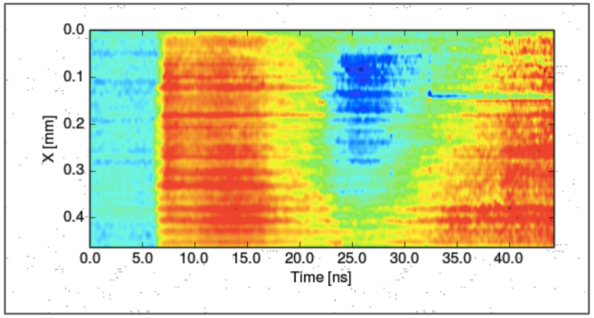
Used Fourier analysis to isolate & resolve wrapped phase signal

$$P(\phi(x,t)+2\pi f_0 x+\delta_0)=\arctan\left(\frac{\mathrm{Re}\left[f(x,t)\right]}{\mathrm{Im}\left[f(x,t)\right]}\right)$$

Converted phase change to velocity via VISAR approximation

$$v(t-\tau_0)=v_i+\kappa F(x,t)+O(\tau_0)$$

$$\kappa=\frac{\lambda_o}{2\tau_0(1+\delta)}$$



Velocity vs. time at all x locations
Smith (J. Appl. Phys. 2013)

Applied to shock breakout time in warm-dense Mo

Questions?