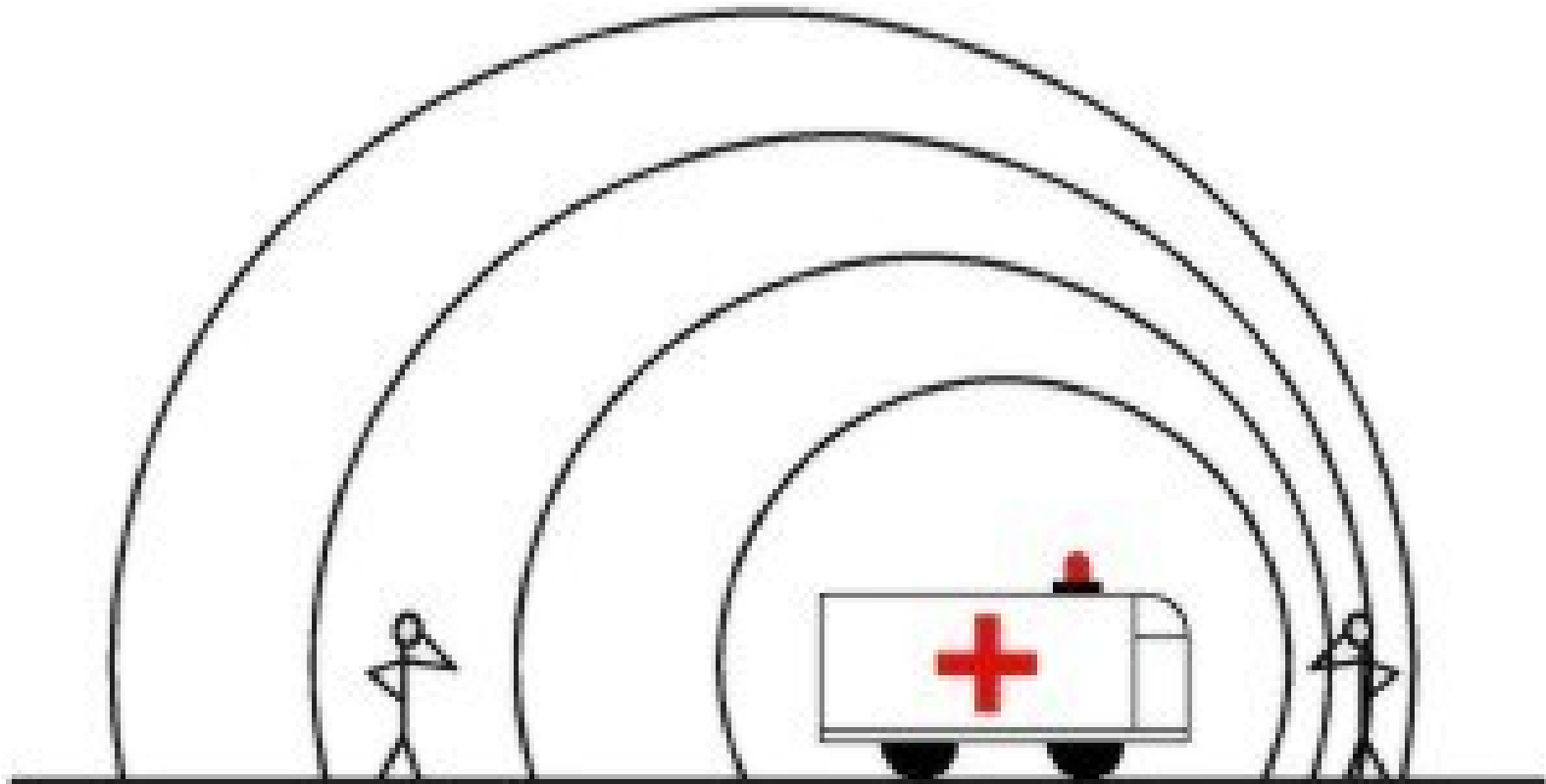


An Introduction to the Theory and Principles of Laser *Doppler* Vibrometry



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What is Laser *Doppler* Vibrometry?



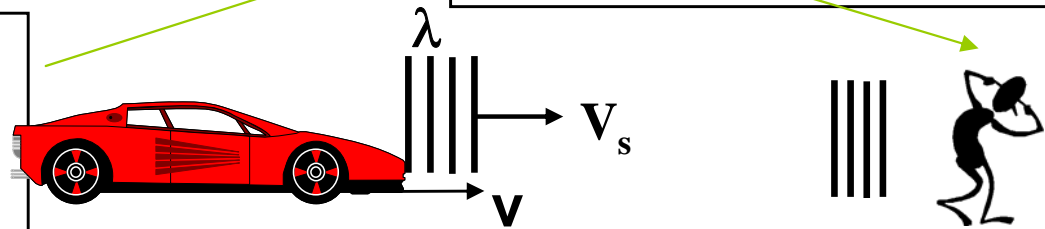
PDV-100 Portable Digital Vibrometer

Laser Doppler Vibrometry is a non-contact, "point and shoot" technology that directly measures the vibration of a test object.

Vibrometers use the Doppler effect.
Analogy: Acoustic Doppler Effect

For car moving at velocity V_c , the observer hears the frequency $f_{obs} = V_s / (\lambda - V/f)$.

Sound emitted from stationary car has frequency $f = V_s / \lambda$



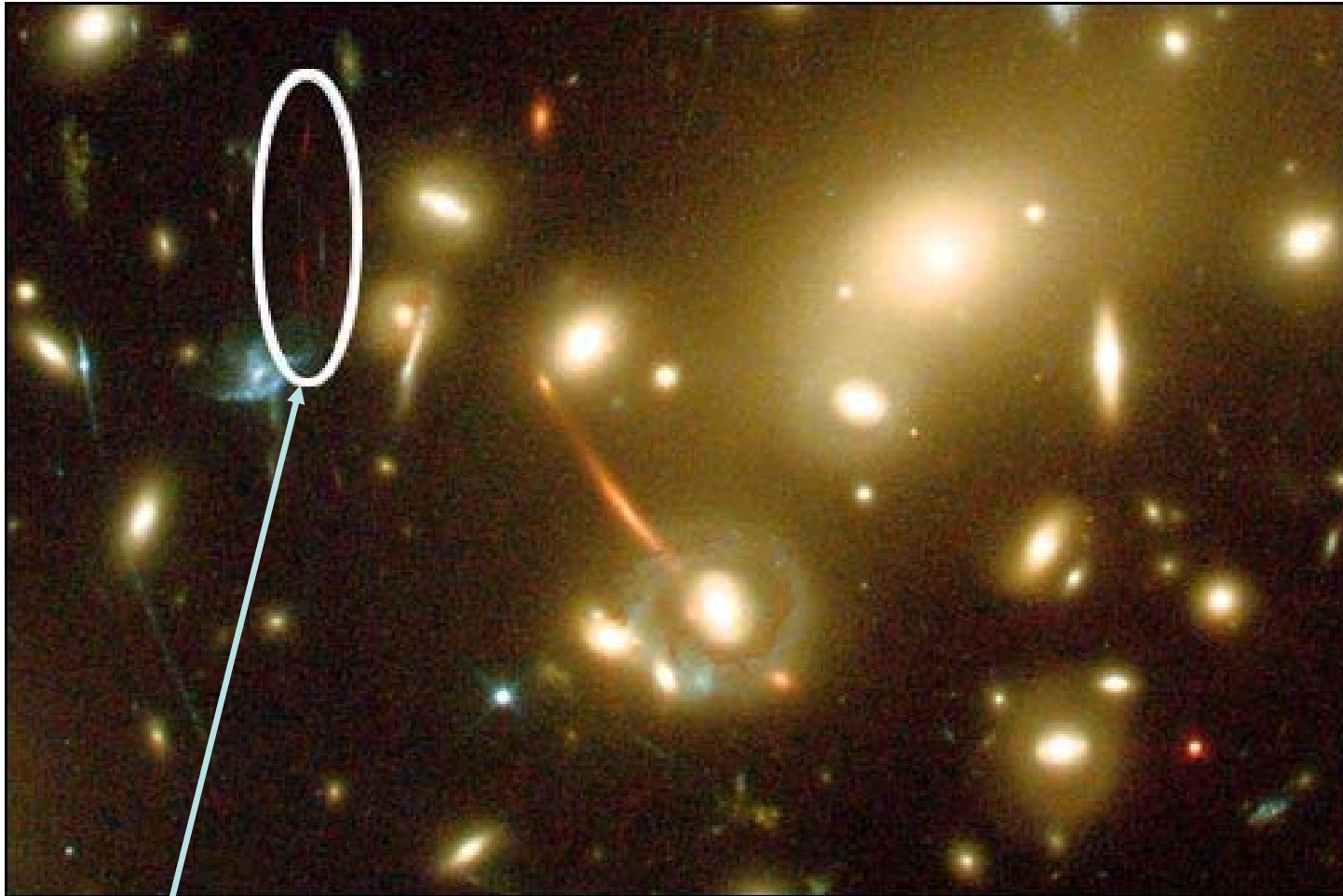
- V_s : velocity of the sound wave
- λ : emitted wavelength
- f : emitted frequency

Emitted frequency f

Observed frequency f_{obs}

Frequency Shift $f_d = V / \lambda$

What is The Doppler Effect

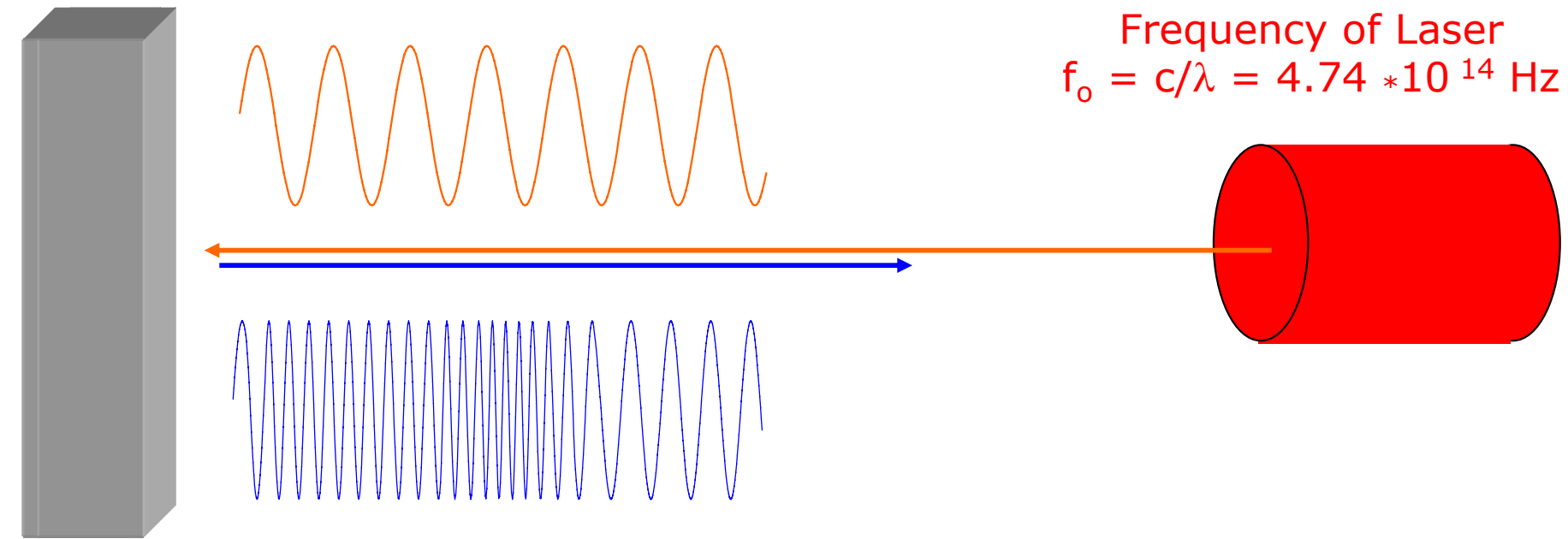


**Galaxy 13 billion light years away
(Universe is about 14 billion years old)**

The Doppler Effect with Laser Light

Object vibrating at velocity V

He-Ne Laser
 $\lambda = 633 \text{ nm}$



Frequency of Laser
 $f_o = c/\lambda = 4.74 \cdot 10^{14} \text{ Hz}$

 Frequency shift by Doppler effect upon reflection

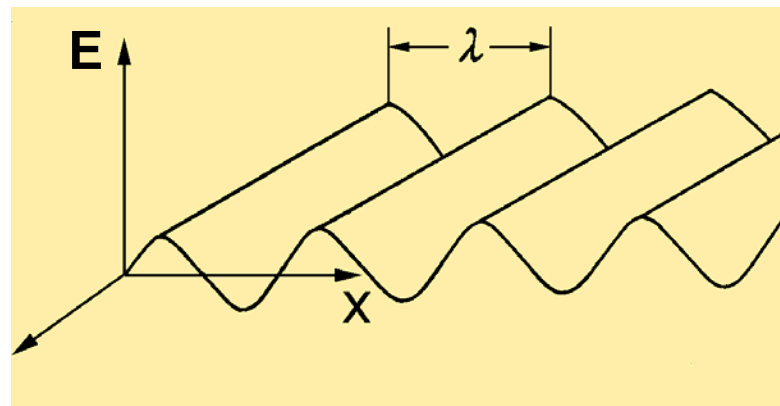
$$\text{Frequency Shift } f_d = 2V / \lambda$$

Lightwaves

A plane wave propagating in the positive x-direction can be described as:

$$\mathbf{E}(x,t) = \mathbf{A}_0 \cos(\omega t - kx)$$

A_0 is the peak amplitude, $\omega=2\pi f$ the angular frequency of the wavetrain and $k=2\pi/\lambda$ the value of the propagation vector in x direction. λ is the wavelength.





Interference

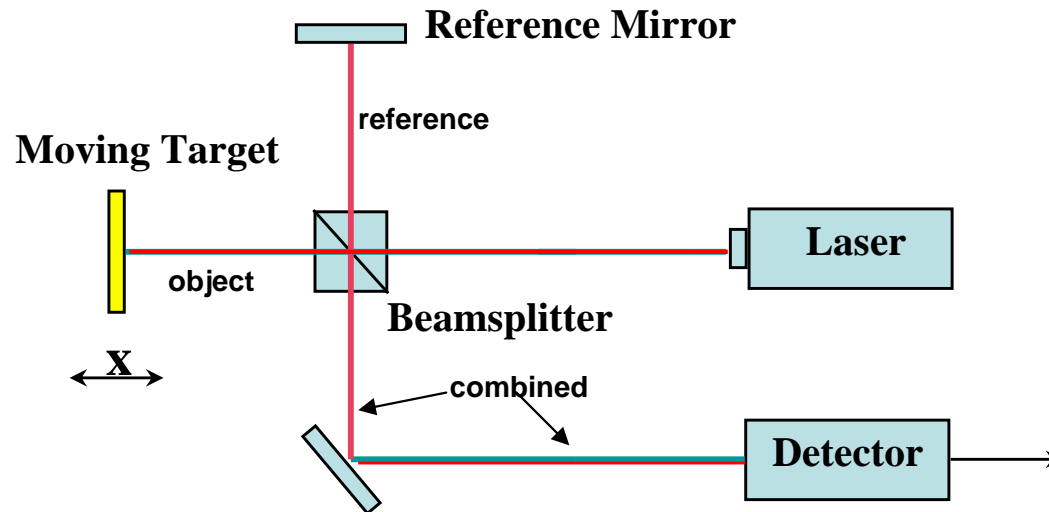
Assume you have two waves E_1 and E_2 that travel in the same direction but that have travelled from the source to the point where they are superimposed via two different routes. The optical path difference (ΔL) produces a phase difference $\Delta\phi = (2\pi/\lambda) \cdot \Delta L$:

$$E_1 = A_0 \cos(\omega t - kx), \quad E_2 = A_0 \cos(\omega t - kx - \phi)$$

$$E_1 + E_2 = 2 A_0 \cos(\phi/2) \cos(\omega t - kx - \phi/2)$$

At $\phi=0$ or $2n\pi$, $n= 1, 2, \dots$ there is a maximum constructive interference. There is destructive interference if ϕ is an odd multiple of π .

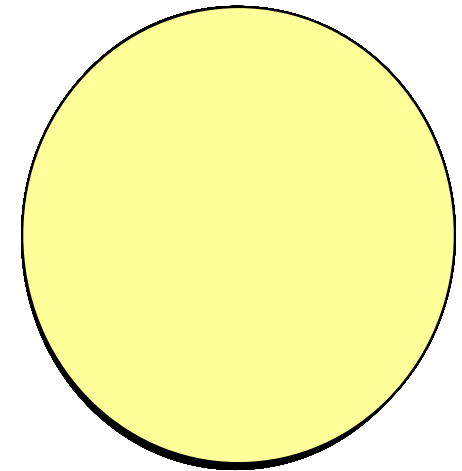
Optical Layout of Classical Interferometer



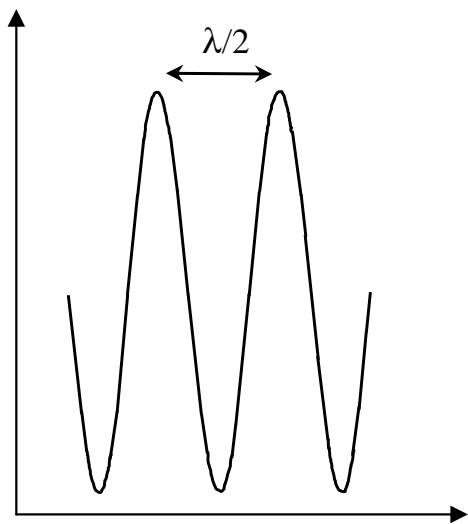
- ➡ **Laser emits spatially and temporally coherent source of light (all photons have same frequency, direction and phase)**
- ➡ **Beam is split into reference and object beams**
- ➡ **Reflected or backscattered beams are recombined at the photo-detector. Phase difference cancels or reinforces light intensity (fringes). Counting fringes gives displacement.**

Signal at the Detector

If the distance x to the target changes continuously, then the light intensity I at the detector varies in a periodic manner. The periodicity is equivalent to a change in x of $\lambda/2$ or the phase ϕ of 2π .



Intensity I



Displacement x

The photodetector is only sensitive to the intensity I of the light.

The signal at the detector has the form:

$$I = I_{\max}/2 \{1 + \cos(\Delta\phi)\}$$

The phase difference $\Delta\phi$ is a function of the optical path difference ΔL according to:

$$\Delta\phi = 4\pi (\Delta L / \lambda)$$

The Doppler Frequency Shift

When the object moves at a constant velocity V , the optical path difference ΔL becomes a function of the time t . $\Delta L = \Delta L(t)$

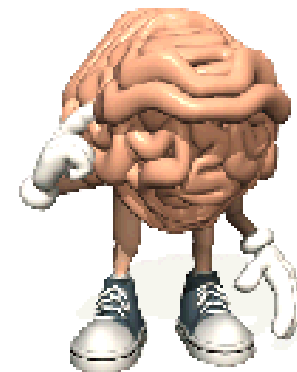
The intensity at the detector changes sinusoidally. The length of this period is $\lambda/2$ and the frequency that is produced as a function of velocity is called Doppler frequency f_D proportional to the velocity

$$f_D = \frac{|V|}{\lambda/2} = \frac{2 * |V|}{\lambda}$$

Since frequency doesn't have any sign, there can be no directional information associated with the velocity derived from f_D .

Problems:

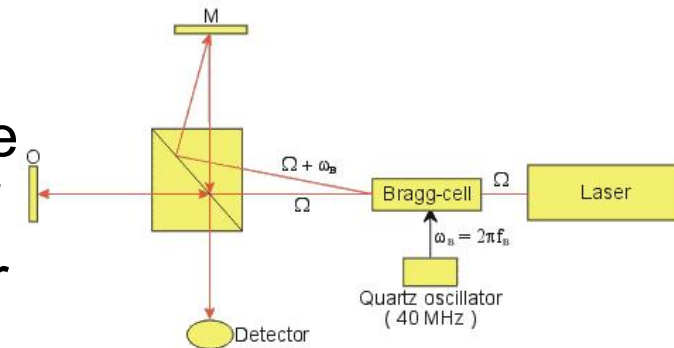
- Since frequency has no sign, we cannot determine the direction of motion by measuring f_D .
- If amplitudes are much less than $\lambda / 2$, the interferometer does not produce complete cycles of intensity change at the Doppler frequency. We need the Doppler frequency to extract the velocity of motion.



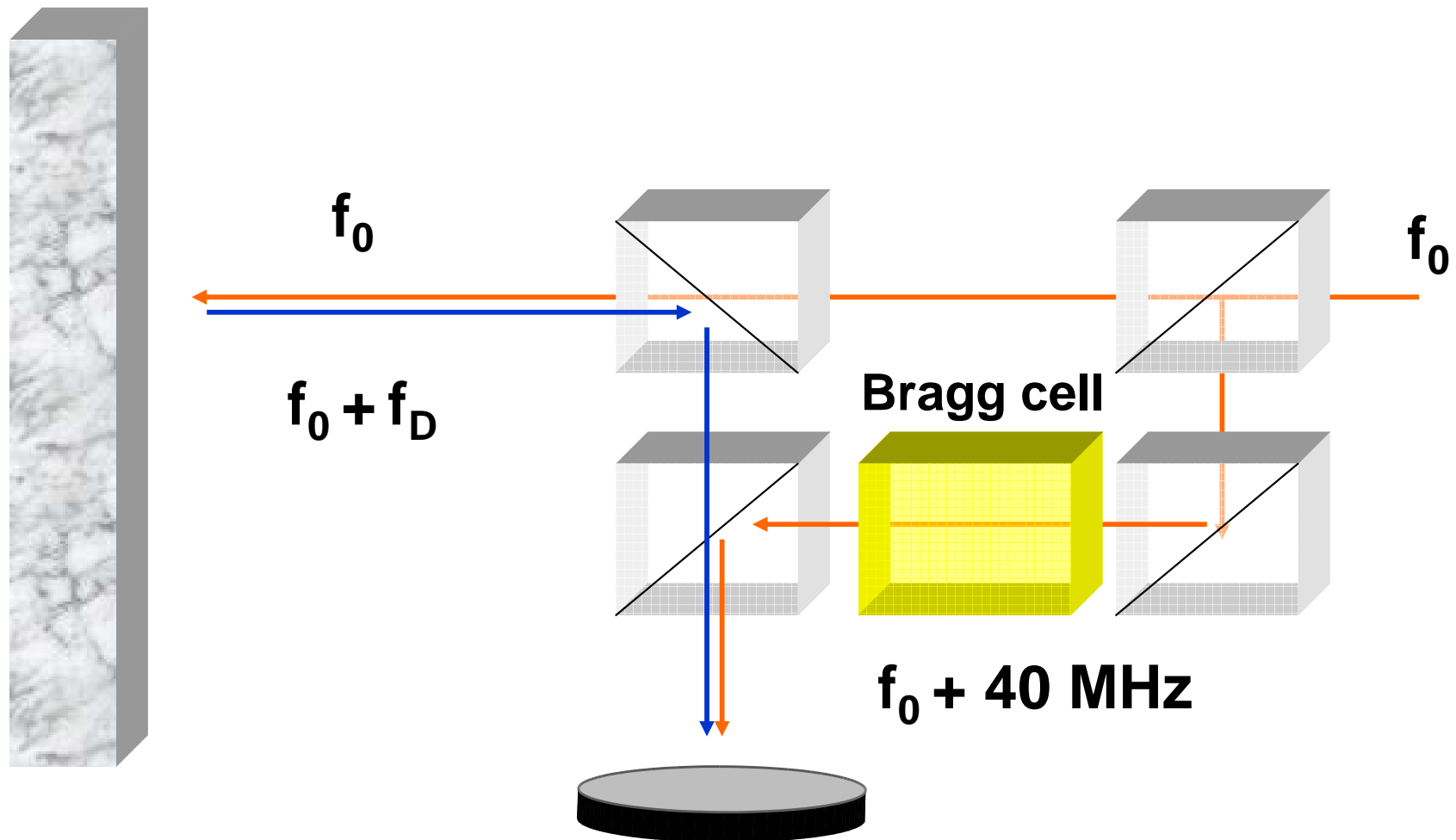
Possible Solutions:

- Add polarizing optics so that the signal at one photodetector either leads or lags the signal at the other photodetector depending on the direction of the surface motion. Signals at each photodetector are in quadrature (sine/cosine) to one another.

- Introduce a frequency shift into the reference beam or object beam of S (Hz) so that there is a constant modulation of intensity at the photodetector for a stationary surface at S (Hz). Modulation frequencies $>S$ indicate surface approaching and $<S$ surfaces moving away.



Heterodyne Interferometer



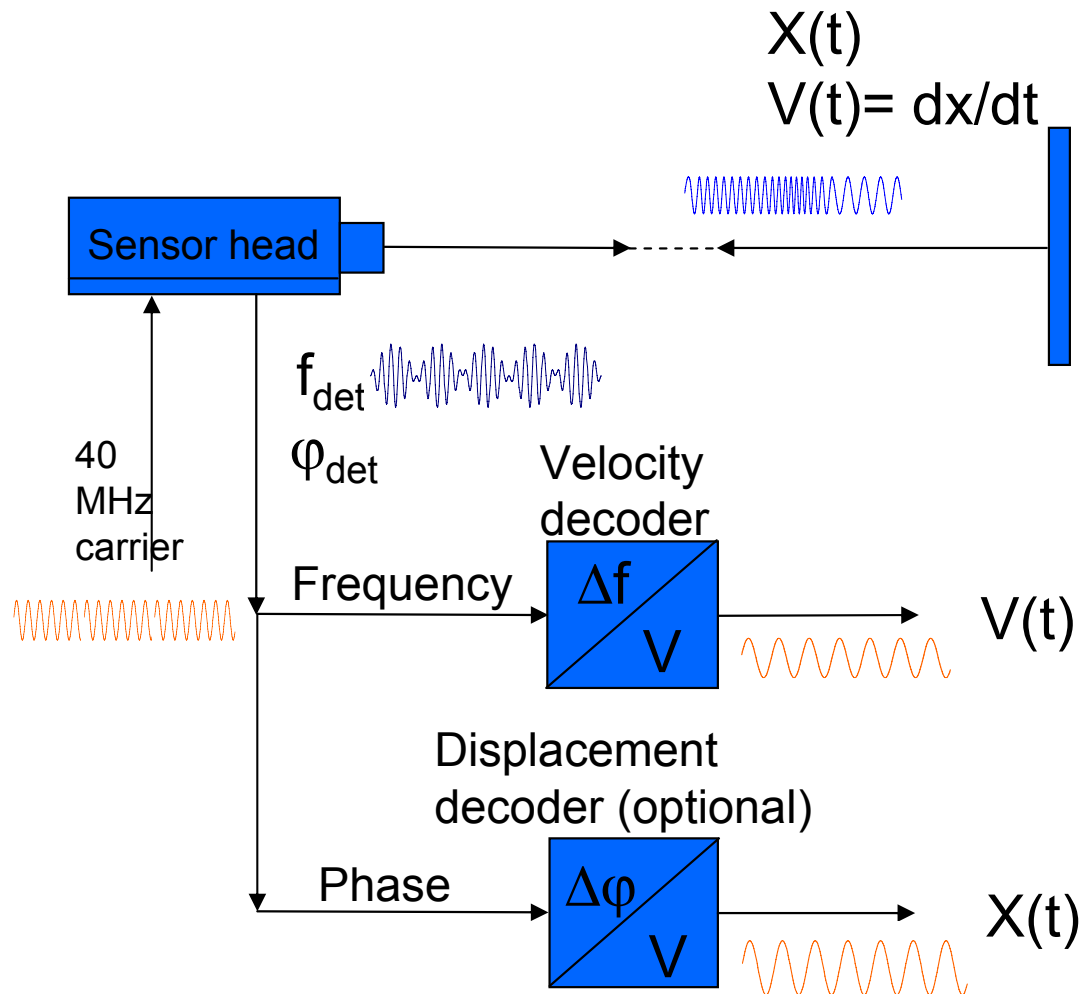
$$f_{\text{detector}} = (40 \text{ MHz} \pm f_D)$$

Heterodyne Interferometer

Advantages over Homodyne Approach:

- Demodulations performed on signals at frequencies well away from hum and other noise emanating from power supplies
- Non-linear behavior of the photodetectors or pre-processing electronics do not affect the integrity of the Doppler information. Measurement signal is defined by zero crossings of the RF carrier. This is true even when the detector signal is clipping as a result of highly reflective surfaces - a major limitation of homodyne interferometry.

Signal Demodulation: Analog and Digital



The signal processor of a Polytec LDV can contain velocity and/or displacement outputs.

f_{det} is decoded to provide a BNC output voltage proportional to instantaneous velocity and ϕ_{det} is decoded to generate a signal proportional to displacement.

Various demodulation schemes are employed including a DSP for digital decoding.

The relationship between Doppler frequency, laser wavelength and velocity is:

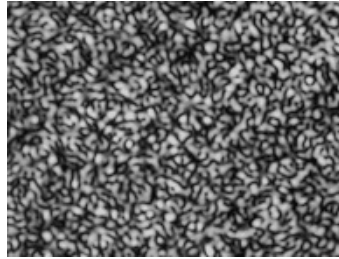
$$\Delta f_D = 2 \cdot \frac{v}{\lambda}$$

For a He-Ne Laser this can be written as:

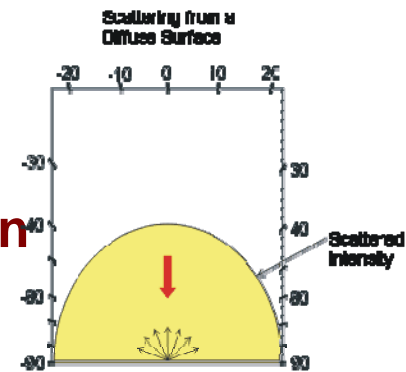
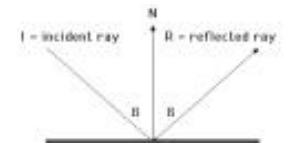
$$\Delta f_D = 3.16 \cdot 10^6 \left[\frac{\text{Hz}}{\text{m/s}} \right] \cdot v \left[\frac{\text{m}}{\text{s}} \right]$$

$$\lambda = 632.8 \text{ nm}$$

Speckles



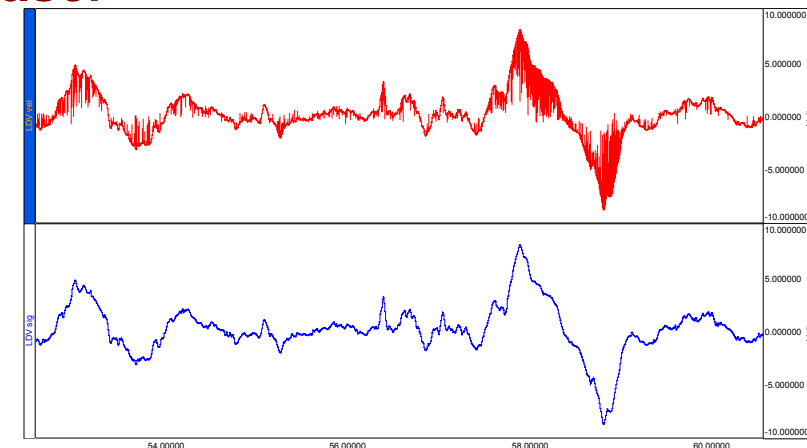
- Specular surfaces – incident and reflected waves are the same angle to the surface
- Diffuse surfaces illuminated by coherent light (laser) generate speckles
- **A “dark“ speckle over the detecting optics can result in low signal-to-noise-ratio**
- Speckles are randomly related in phase to one another
- Speckles will move and “boil“ over the detecting optics in response to motion of the surface
- **A phase change between speckles can result in a noise spike for velocity and a signal jump for displacement**



Speckles

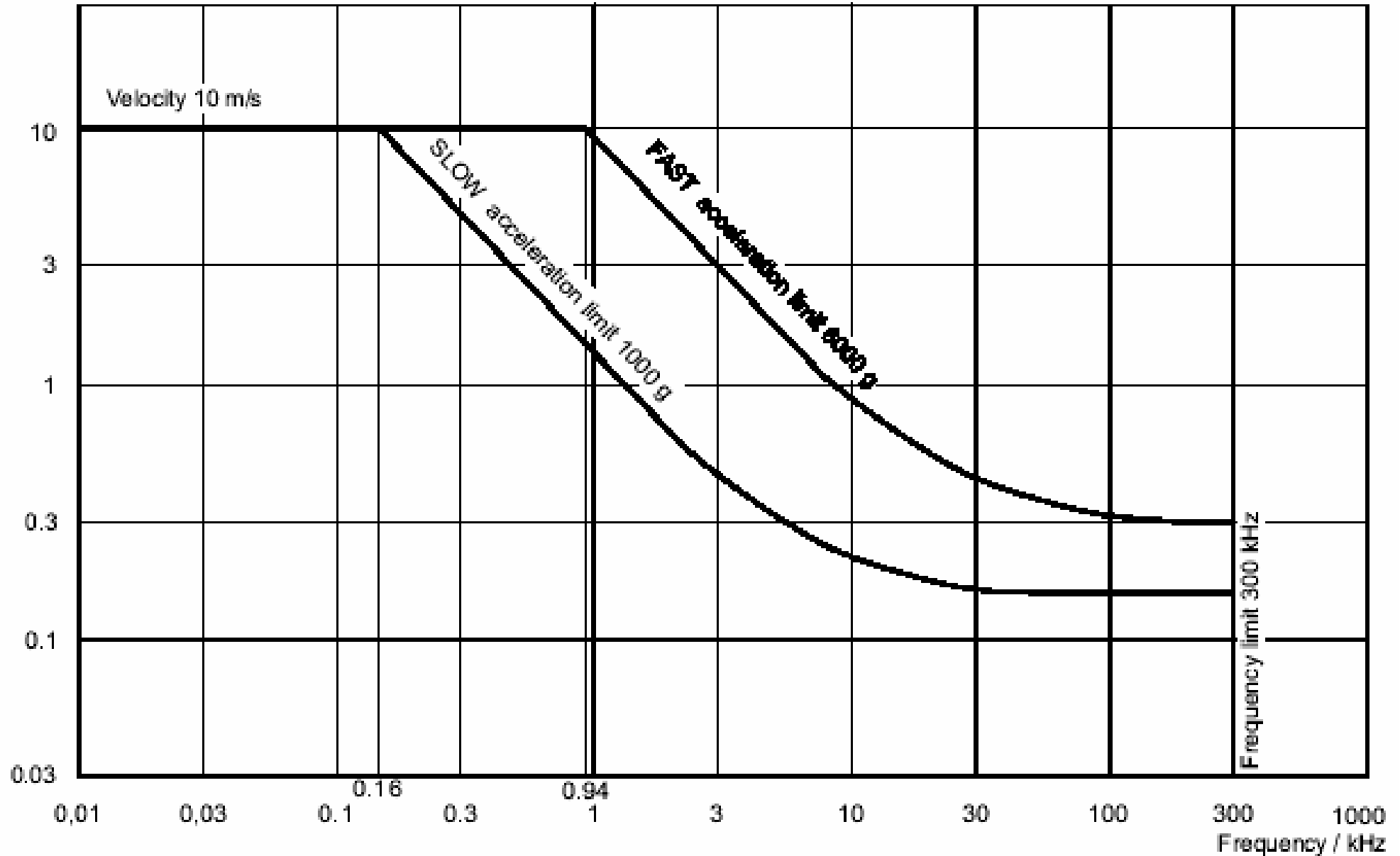
- Solutions for a dark speckle:
 - **Select a sensor head, decoder type or range setting that has better optical sensitivity**
 - **If possible move to a visibility maximum standoff**
 - **Treat the surface**
 - **Tweak position of laser to find a bright speckle either manually or using automated speckle tracking and Signal Enhancement algorithms in PSV**

- Solutions for speckle noise produced by a moving surface:
 - **Minimize motion in laser direction**
 - **Follow the motion by moving the laser**
 - **Despeckling algorithms**
 - **Select tracking filter in controller**



Tracking Filter

Velocity / m/s



Polytec Performance Summary

- Vibration frequency range DC to 30 MHz
- Maximum amplitudes to 30 m/s
- Analog decoder resolution down to $0.05 \mu\text{m/s}/\sqrt{\text{Hz}}$
- DSP decoder resolution down to $0.01 \mu\text{m/s}/\sqrt{\text{Hz}}$
- Pure digital decoding resolution 1 – 2 pm
- Laser spot size (spatial resolution) down to $1 \mu\text{m}$
- “Eye-safe“ Class II visible laser