Intuitive description and experimental proof tests of Optical Ranging

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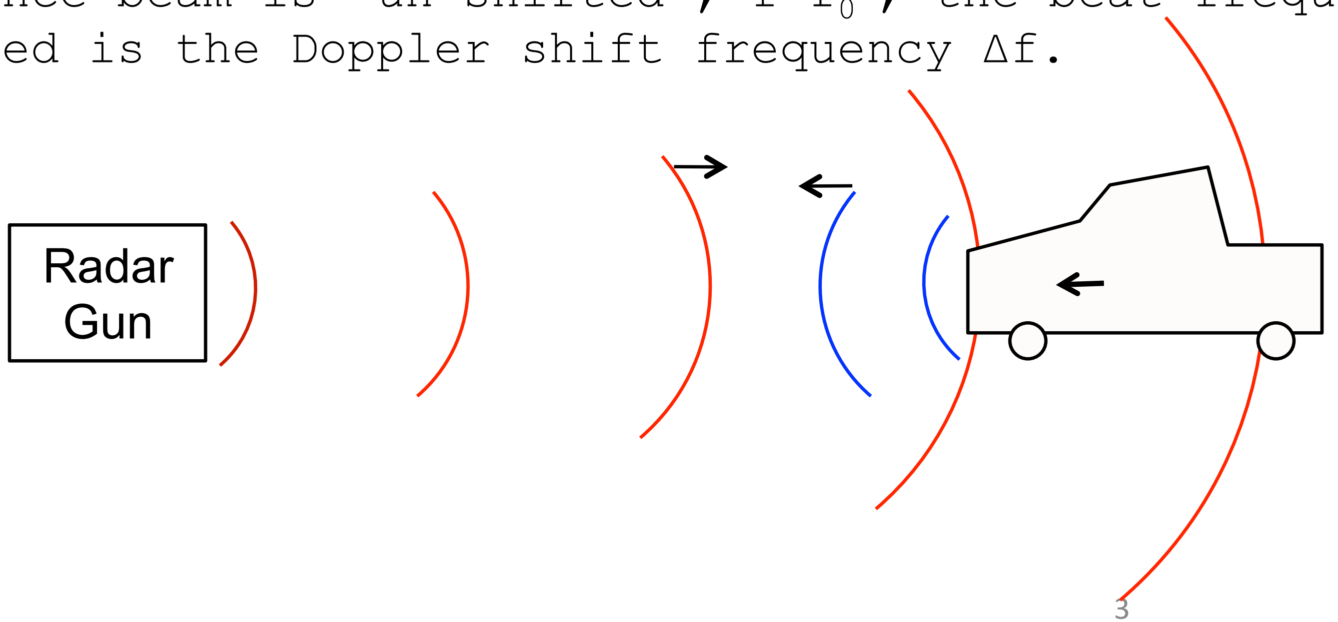
Outline

1. Attributes of optical velocimetry & enhancement from optical ranging.
2. Optical ranging implementations and proof-of-principle work.
3. Summary

Optical heterodyne velocimetry

- An optical beam at f_0 is directed at a target; the reflection is Doppler shifted (e.g., $\Delta f=2vf/c=1.3$ GHz/(km/s)).
- The return beam is combined with a reference beam.
- Detection (e.g., with a photodiode) of the combined beams reveals the beat frequency between the two beams which is simply related to the speed of target. If the reference beam is "un-shifted", $f=f_0$, the beat frequency detected is the Doppler shift frequency Δf.

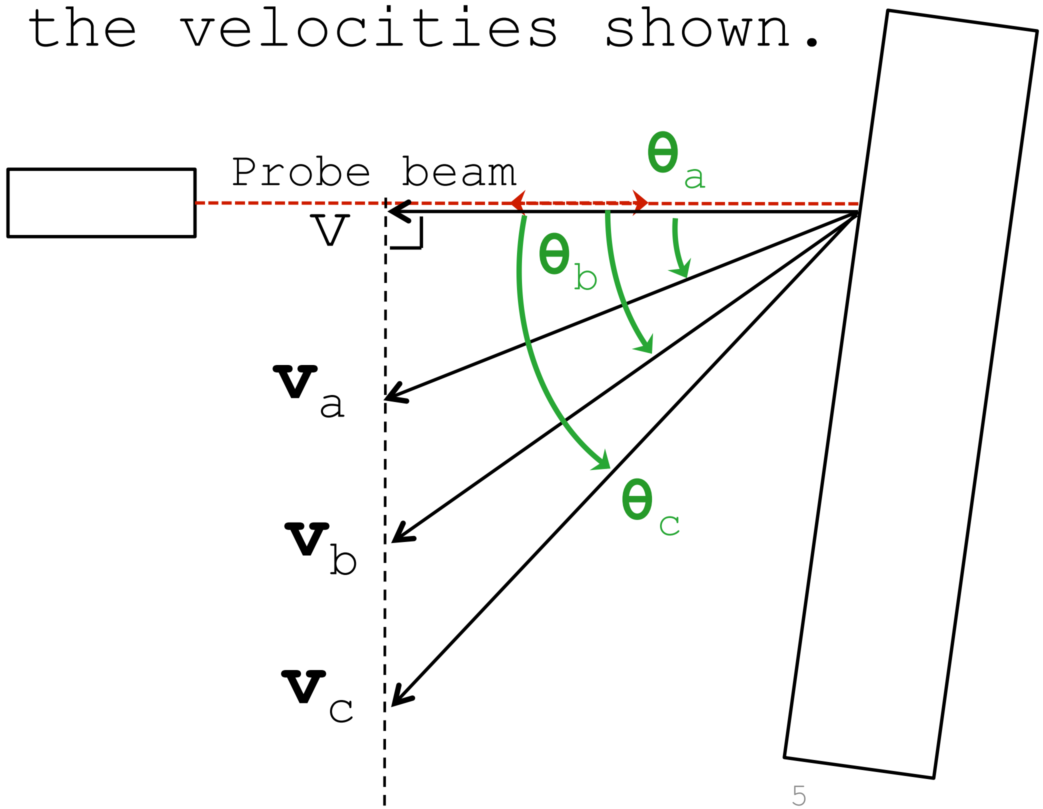


Attributes of optical heterodyne velocimetry

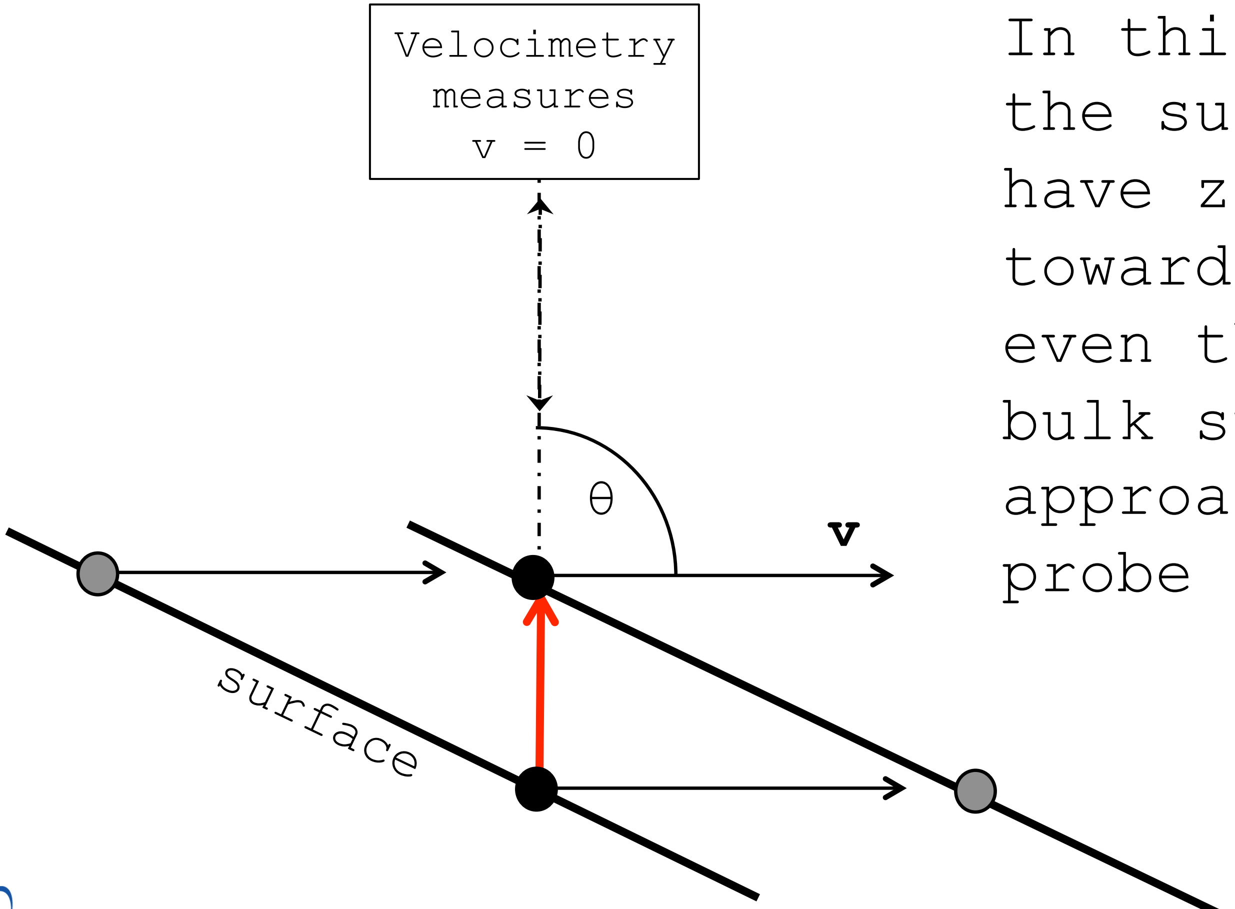
1. Unambiguous interpretation: measures the component of scatterer velocity along the beam, $v_{scatterer} * \cos(\theta)$.
2. Capable of high bandwidth.
3. Robust extraction of signal from noise with sliding power spectrum.
4. Can measure multiple velocities simultaneously.
5. Can measure the bulk velocity of a cloud of particles – in principle, no solid surface required.

Optical velocimetry measures the component along the beam of the velocity vector of a point on a surface.

This means the same speed $v = v_i\cos(\theta_i)$ is measured for all the velocities shown.

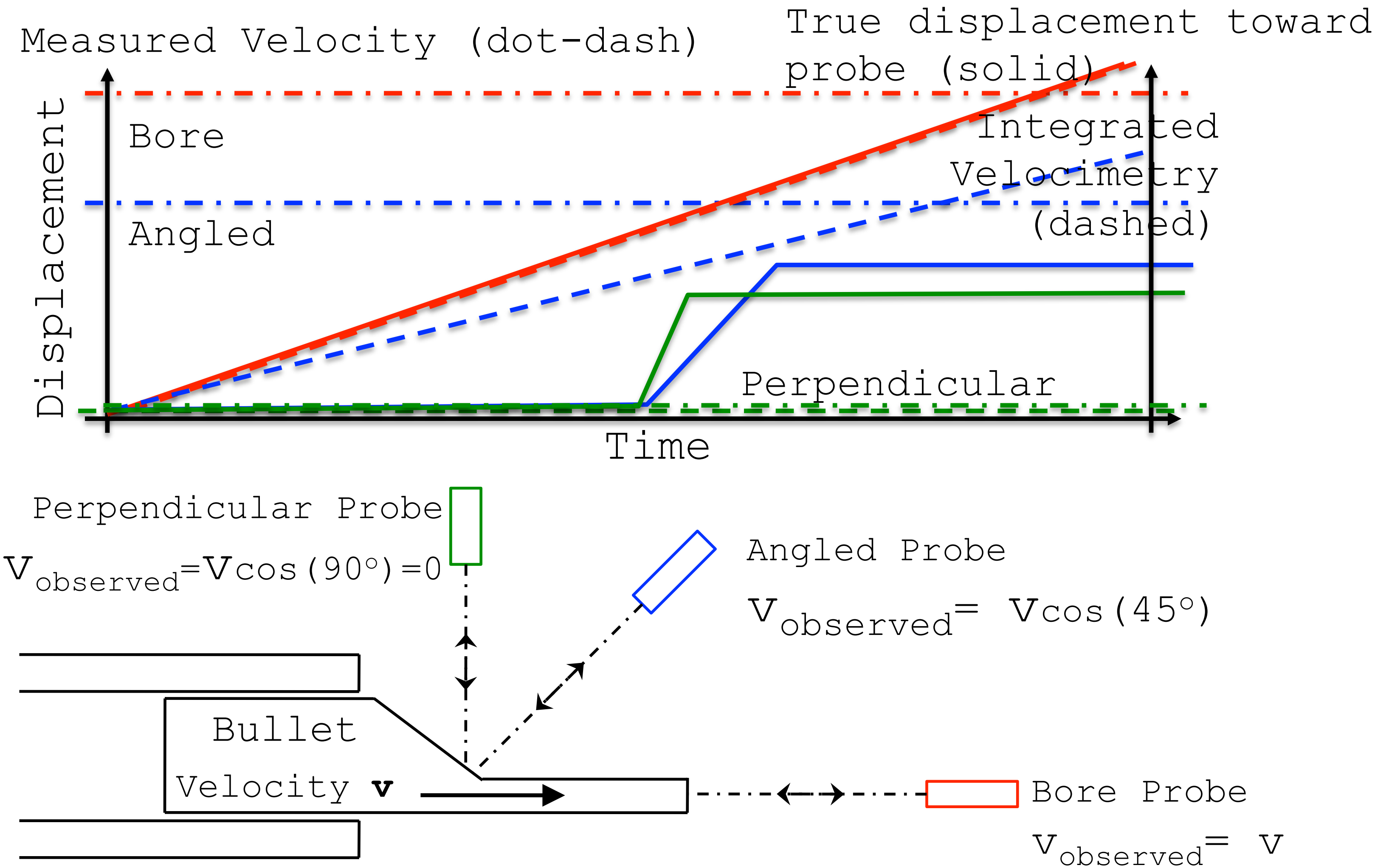


This unambiguous interpretation comes at the cost of missed material displacement



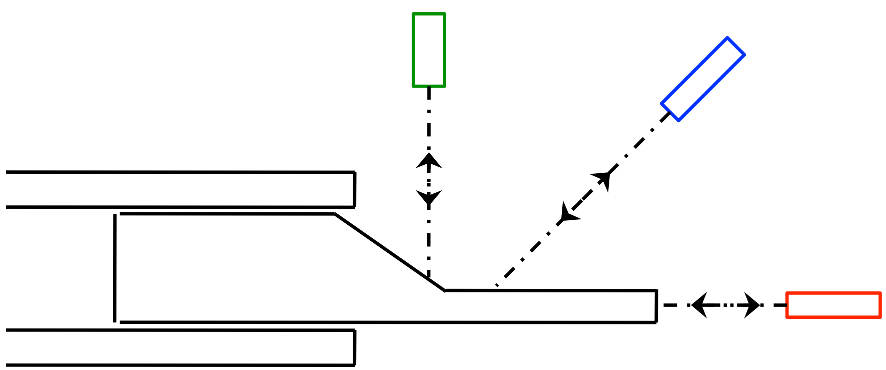
In this example, the surface points have zero velocity toward the probe even though the bulk surface is approaching the probe (red arrow).

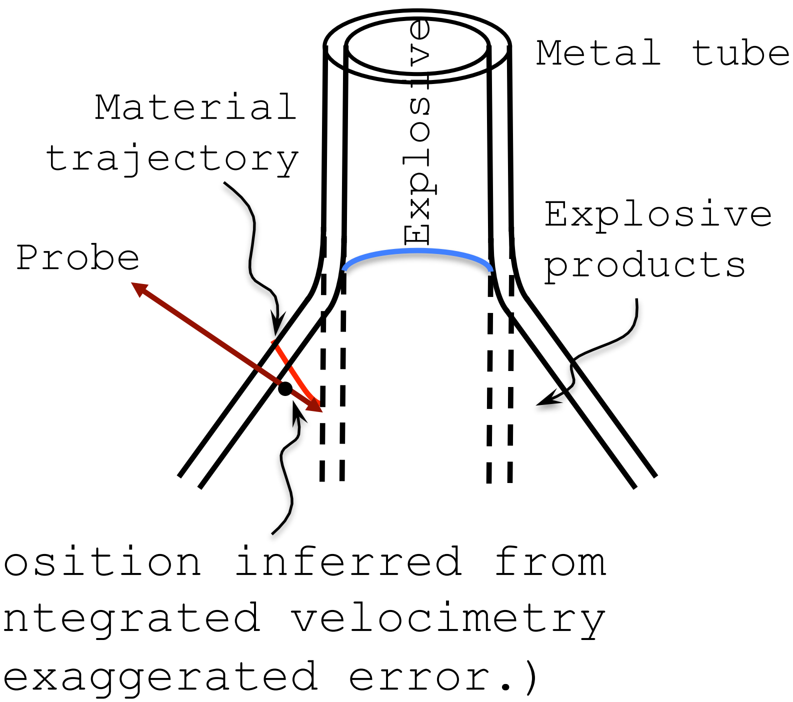
Example of missed material approach in a real experiment



We cannot constrain material position with velocimetry alone

A large number of velocity measurements along with knowledge of initial conditions will constrain the material position of a rigid object. However, this has not been demonstrated for objects that are deforming, where the presence of shear motion is likely. From the above, we know shear motion is not measured.

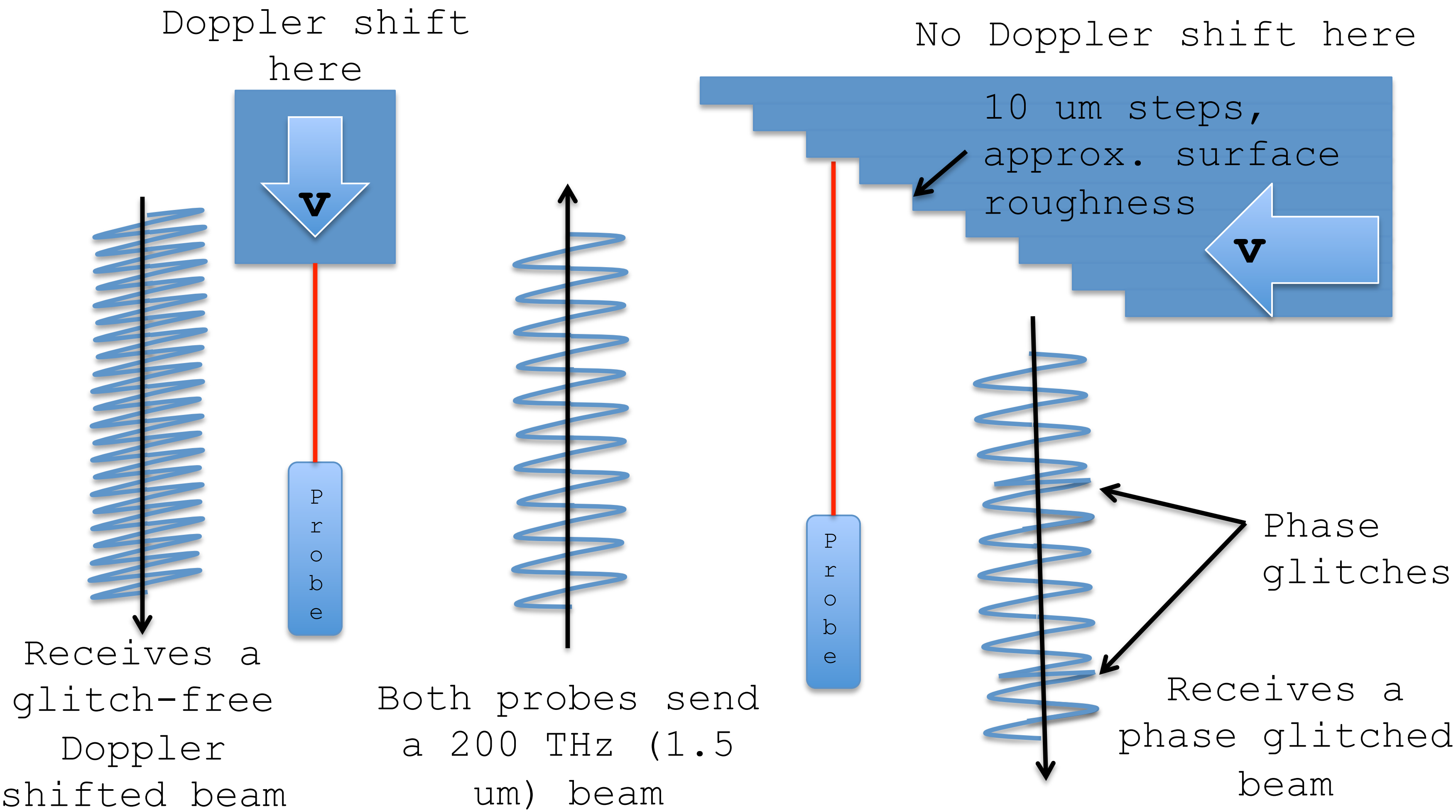




Optical ranging = techniques to track the full target approach

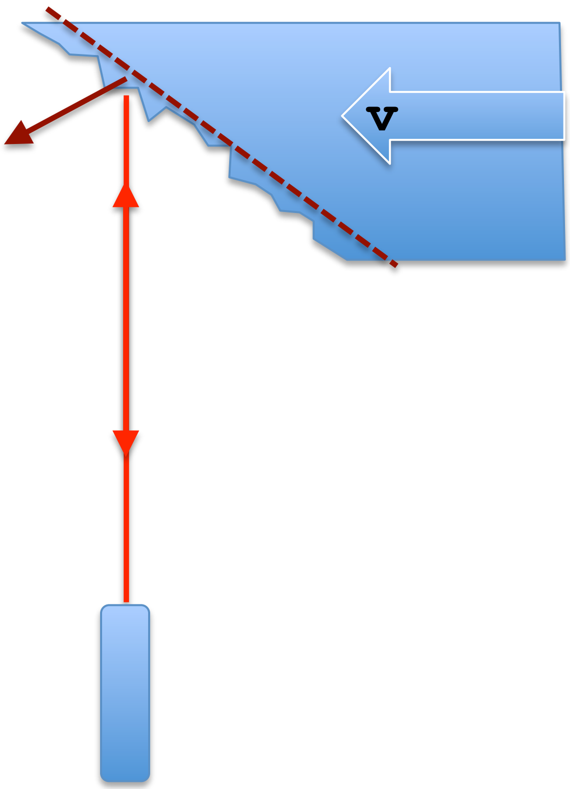
- Goal: Create an optical measurement that measures the *surface displacement* at <0.1 mm resolution and >1 MHz bandwidth.
- A resolution of 0.1 mm on an approach of 1 km/s is equivalent to a 100 ns time blur (toward the high end of what we want).
- A 1 MHz sample rate would allow 100 measurements in a 100 μs.

Lateral motion is undetected because there are phase glitches and no Doppler shift



Phase glitches are unavoidable: receiving light in the non-specular direction requires surface roughness >λ

- Polishing surface does not help because there would be no return light to the probe.
- If we want to track the surface position, we need to modify the carrier beam.



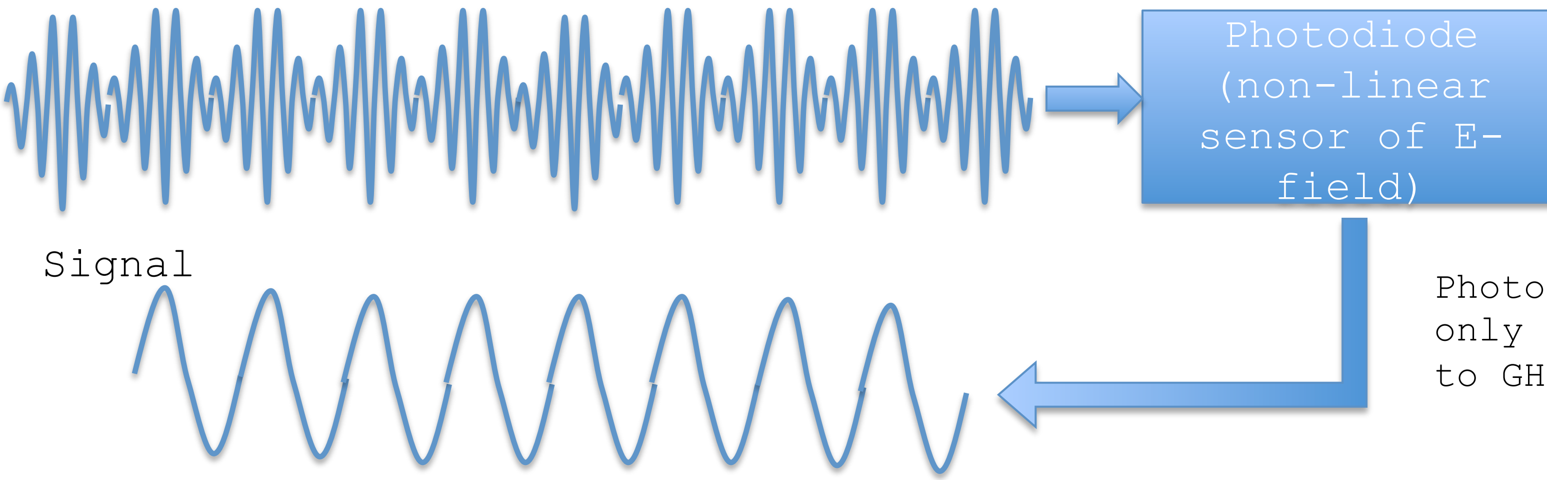
Amplitude modulation method: create an effective wavelength > surface roughness

Carrier freq: ~200 THz (1.5um)
AM freq: Several GHz

Same as Optical Velocimetry. Will diffusively reflect (surface roughness >> wavelength).

Sensitive to surface position (i.e., surface roughness << wavelength)

Carrier modulated with Signal



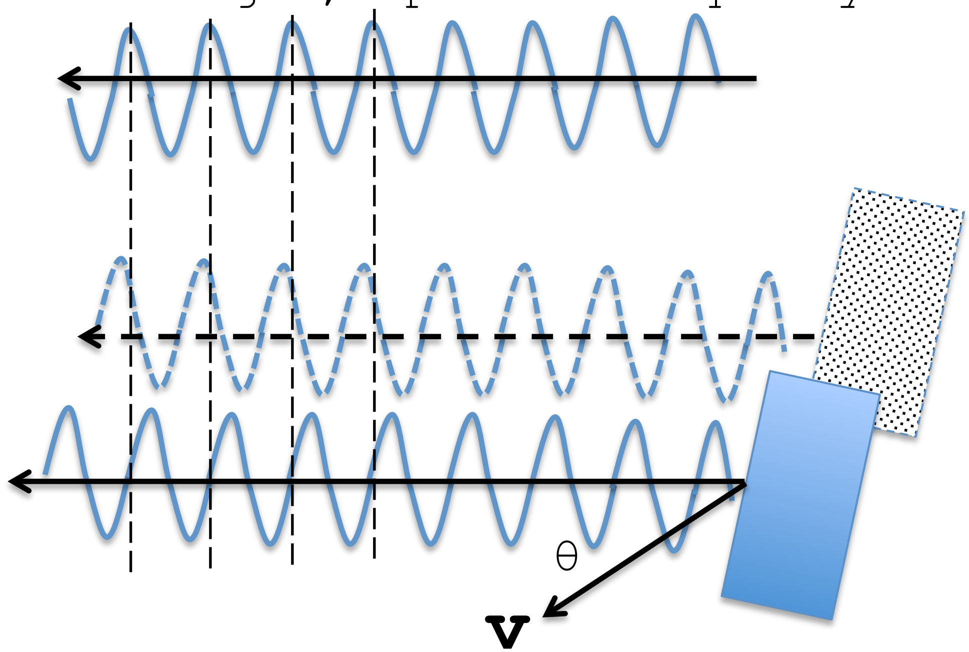
Photodiode only responds to GHz signal.

Note: Ratio of Carrier and AM frequencies not to scale.

Optical ranging with amplitude modulation phase

The phase difference in the amplitude modulation between the reference and return signals gives position. In practice, use change in phase (displacement.)

1 GHz AM reference (local oscillator) signal (30 cm wavelength, optical frequency not shown)

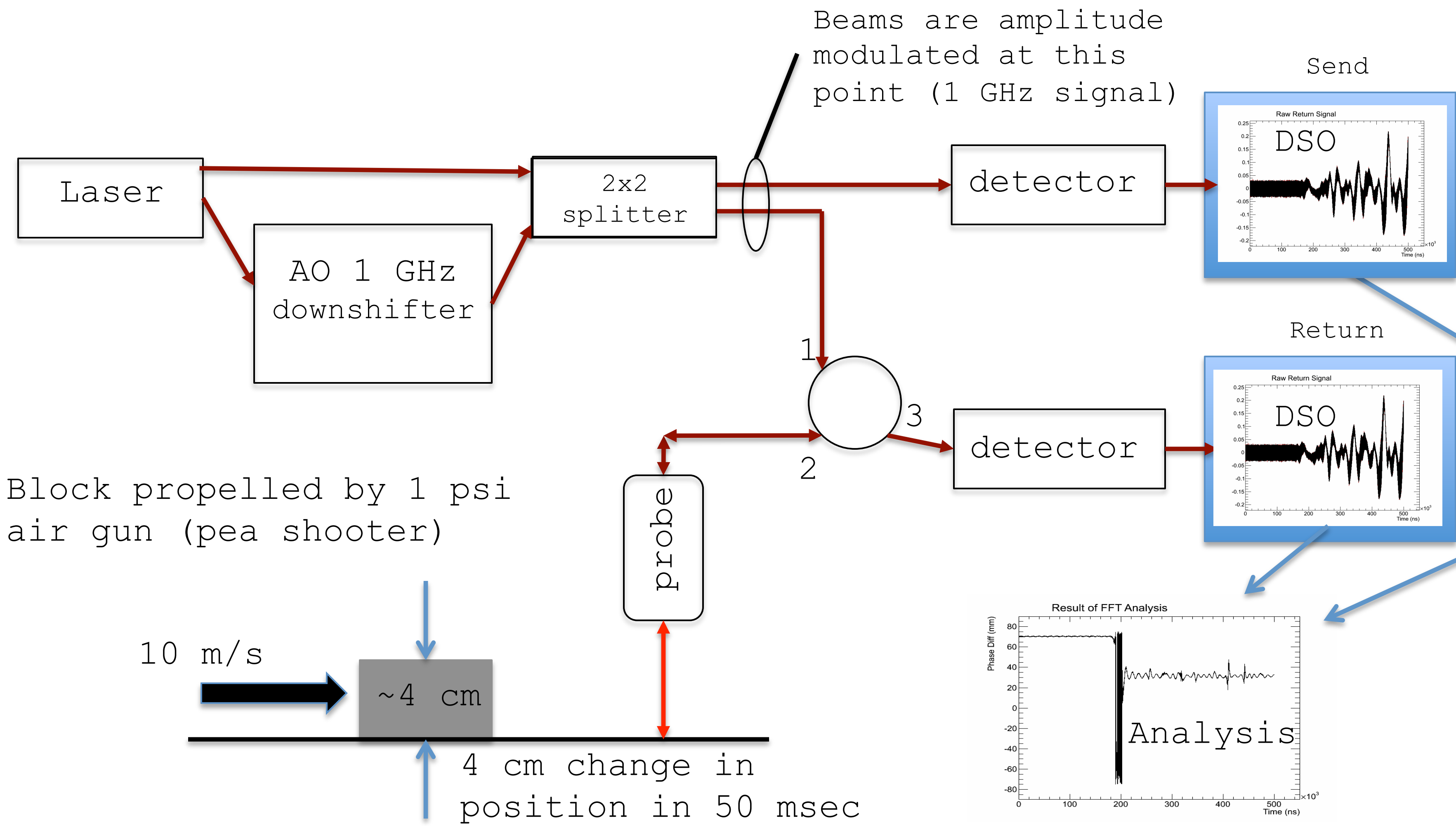


Return AM signal shifts in phase as object moves; phase glitches are small compared to the AM wavelength

Optical Ranging Rules

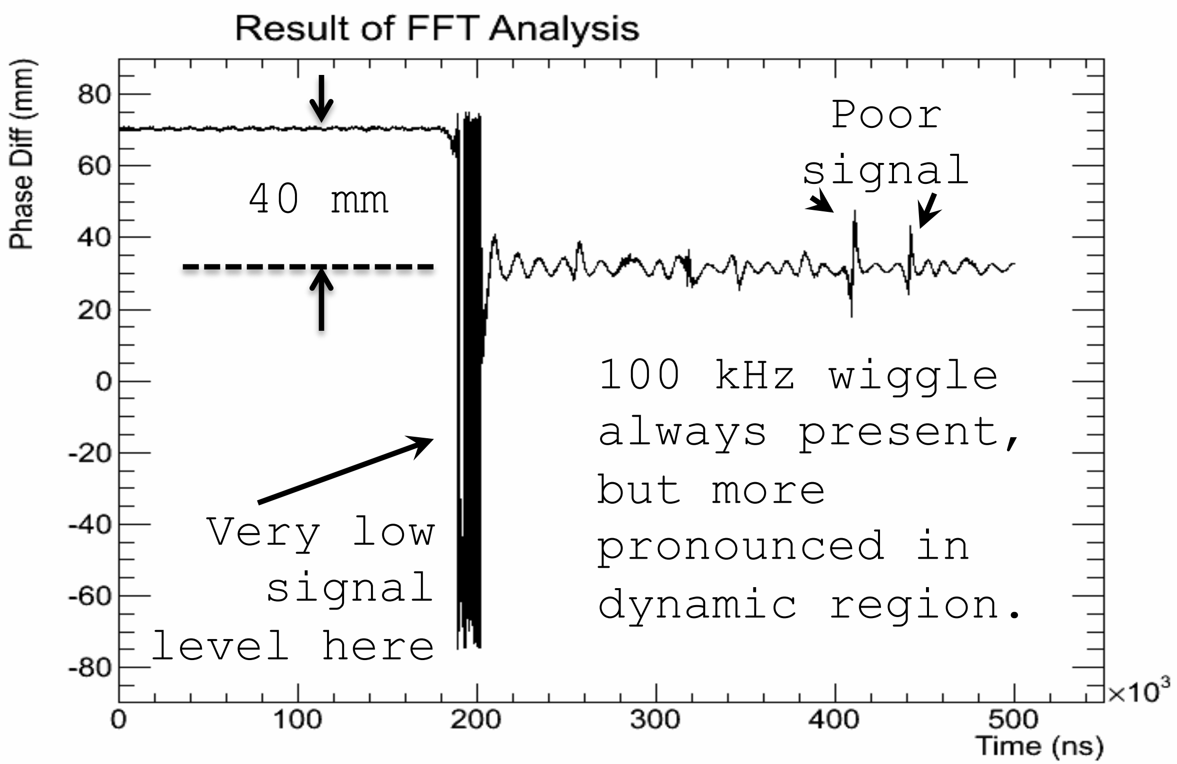
- Measurement Bandwidth:
  - Upper limit is the AM frequency
  - In practice, will average over many cycles (i.e., a GHz AM signal will give a MHz measurement bandwidth)
- Resolution:
  - Depends on Bandwidth of phase comparator, the AM freq., & signal/noise ratio at the AM freq.
  - Should be insensitive to noise at other frequencies.

First Proof-of-Concept



Proof-of-Concept: Results

- The 4 cm step is successfully tracked.
- Measurement accuracy is <1 mm except for a 100 kHz wiggle.



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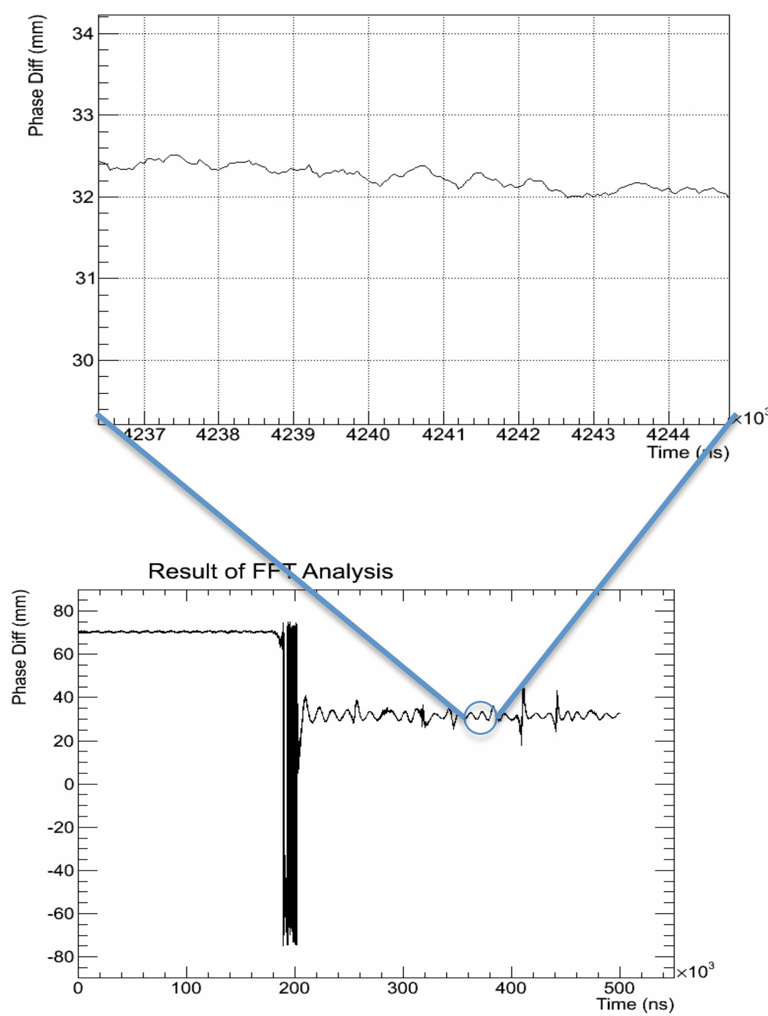
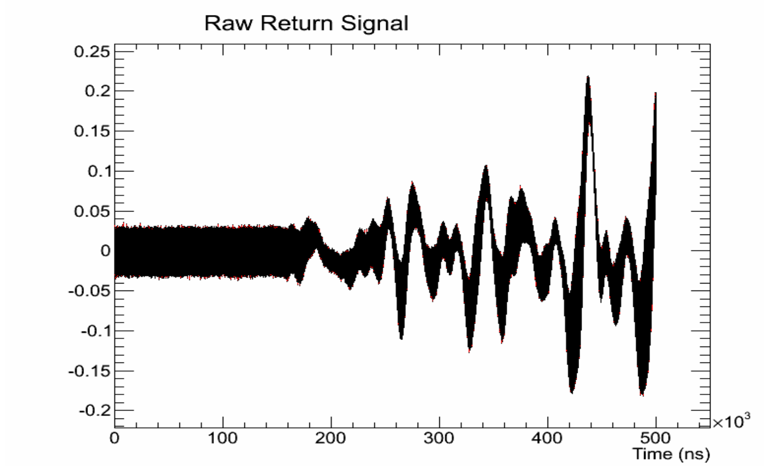
Proof-of-Concept: Results



- The method appears quite robust in the presence of optical noise.
- Except for 100 kHz wiggle, ~0.2 mm resolution.

Lot of low freqs. in our raw signal.



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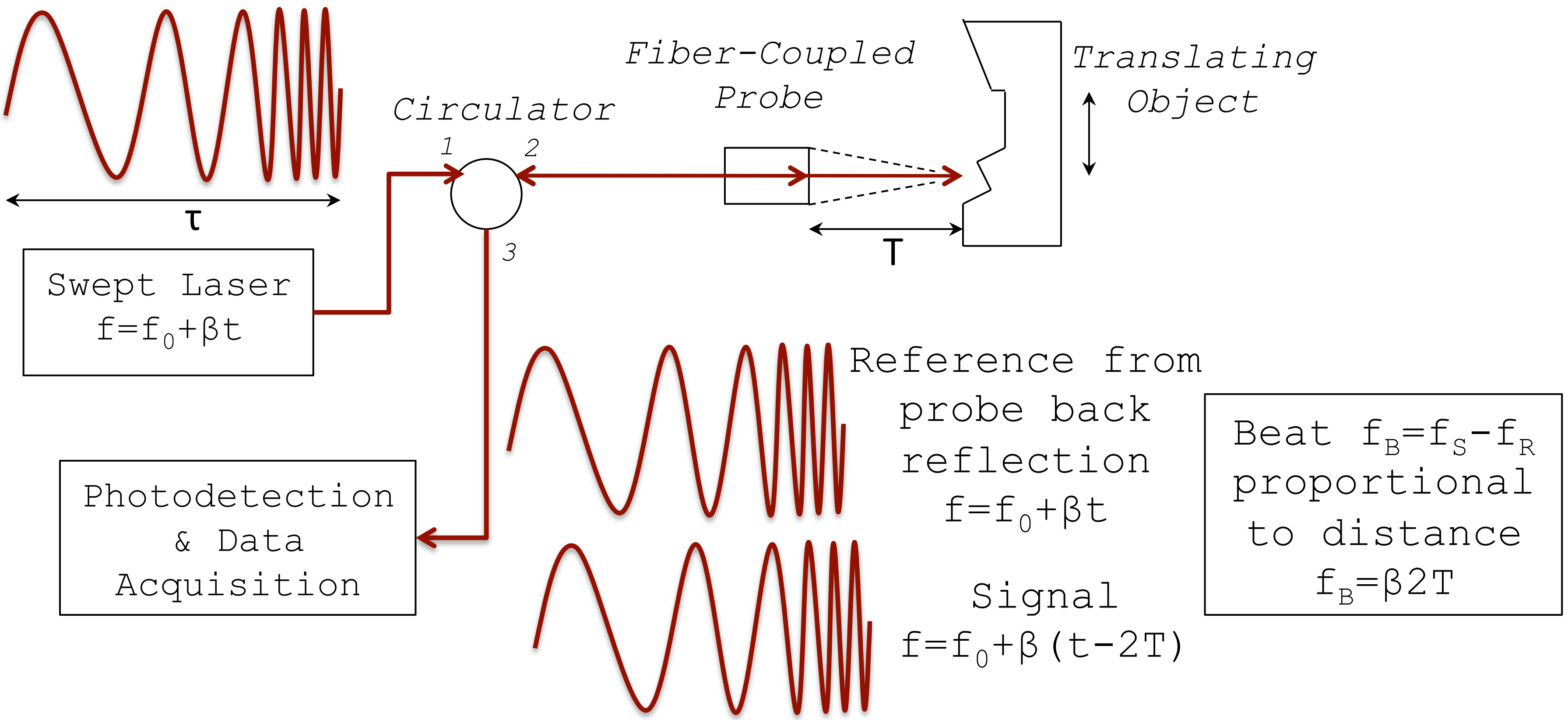
Summary of amplitude modulation approach

- The Optical Ranging method presented here complements Velocimetry and can coexist on the same probe with PDV.
- Our initial proof-of-concept was successful, and we expect our resolution to improve.

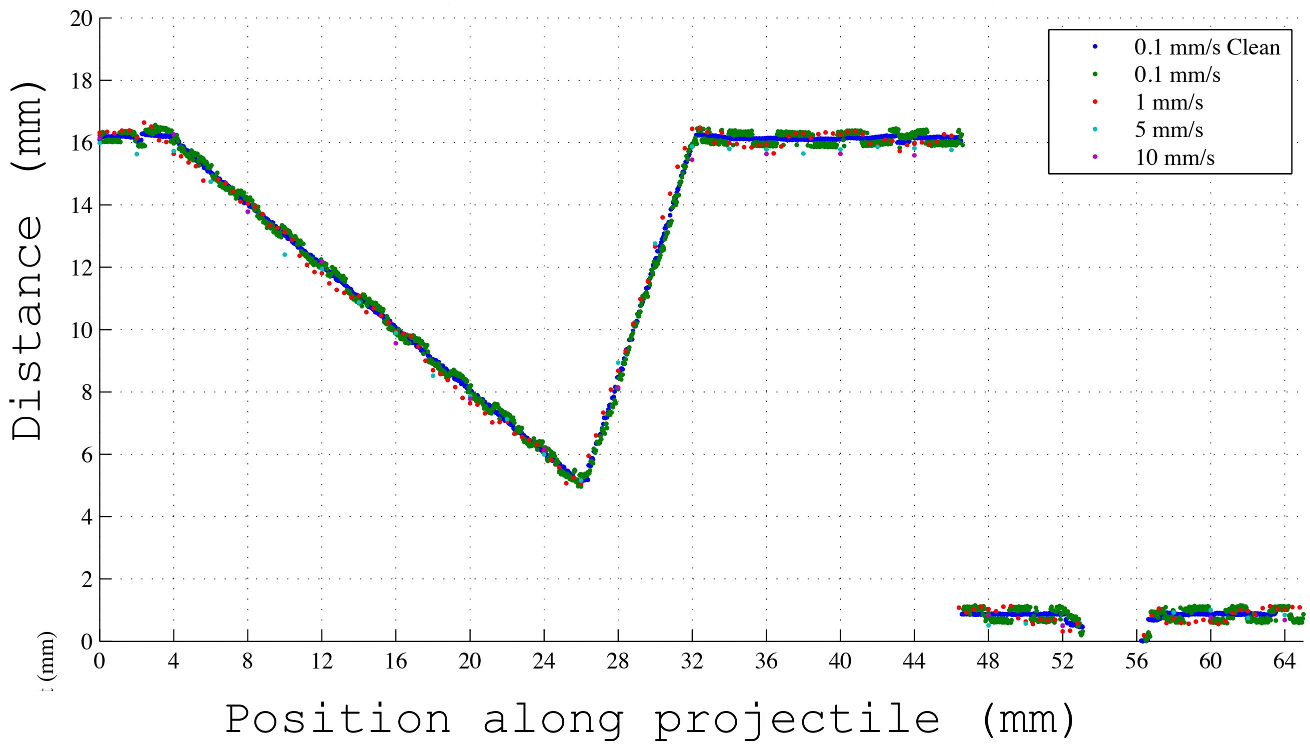
Optical ranging using frequency sweeps

- Goal: incorporate Insight's swept laser into a simple test-bench to demonstrate capability in measuring the absolute distance between the fiber probe and the translating object.



Preliminary swept frequency results motivating demo test

- Mounting the projectile on a translation stage, the swept laser is shown to provide an absolute position measurement (note: more than a displacement measurement.)
- Therefore capable of tracking surfaces whose orientation or trajectory provide misleading PDV results



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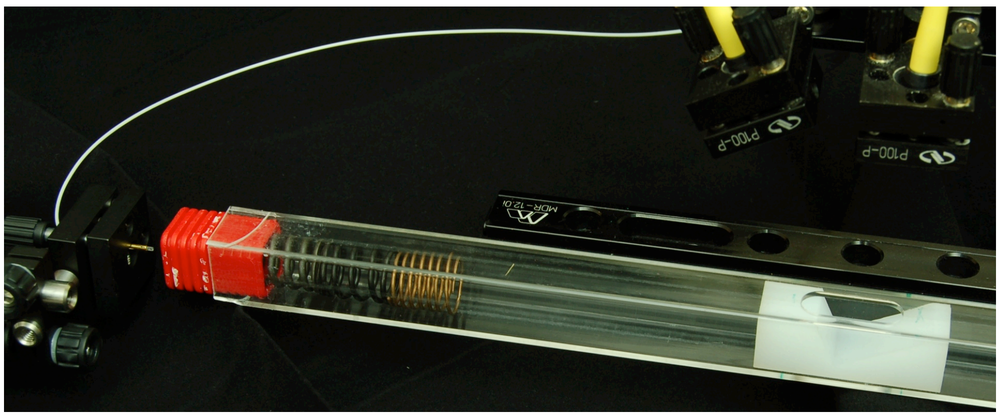
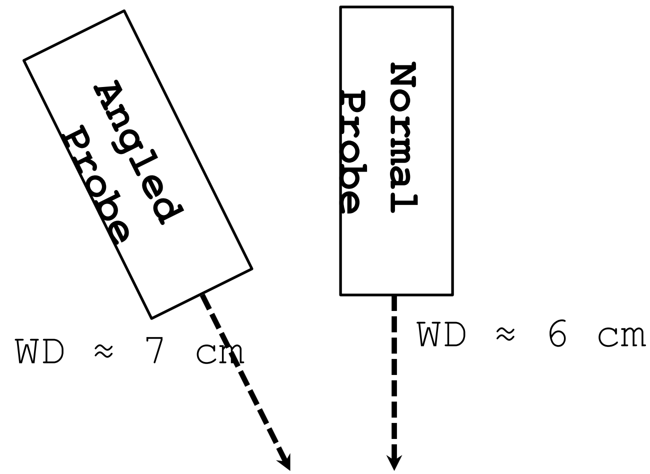
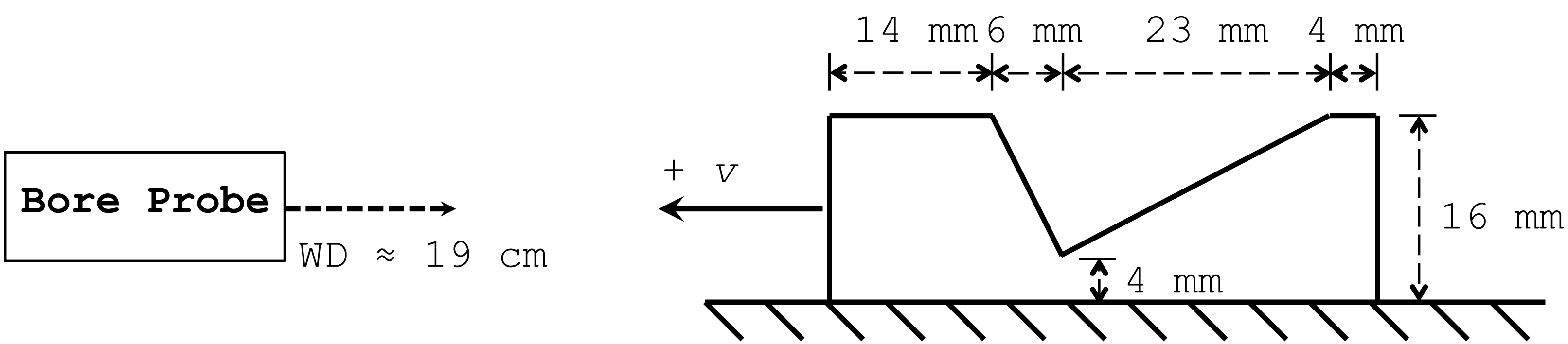
Demonstration test with the LANL pea-shooter using PDV and swept laser simultaneously

The arrangement of probes and the geometry of the projectile offer insight into the capabilities of the sensing methodology







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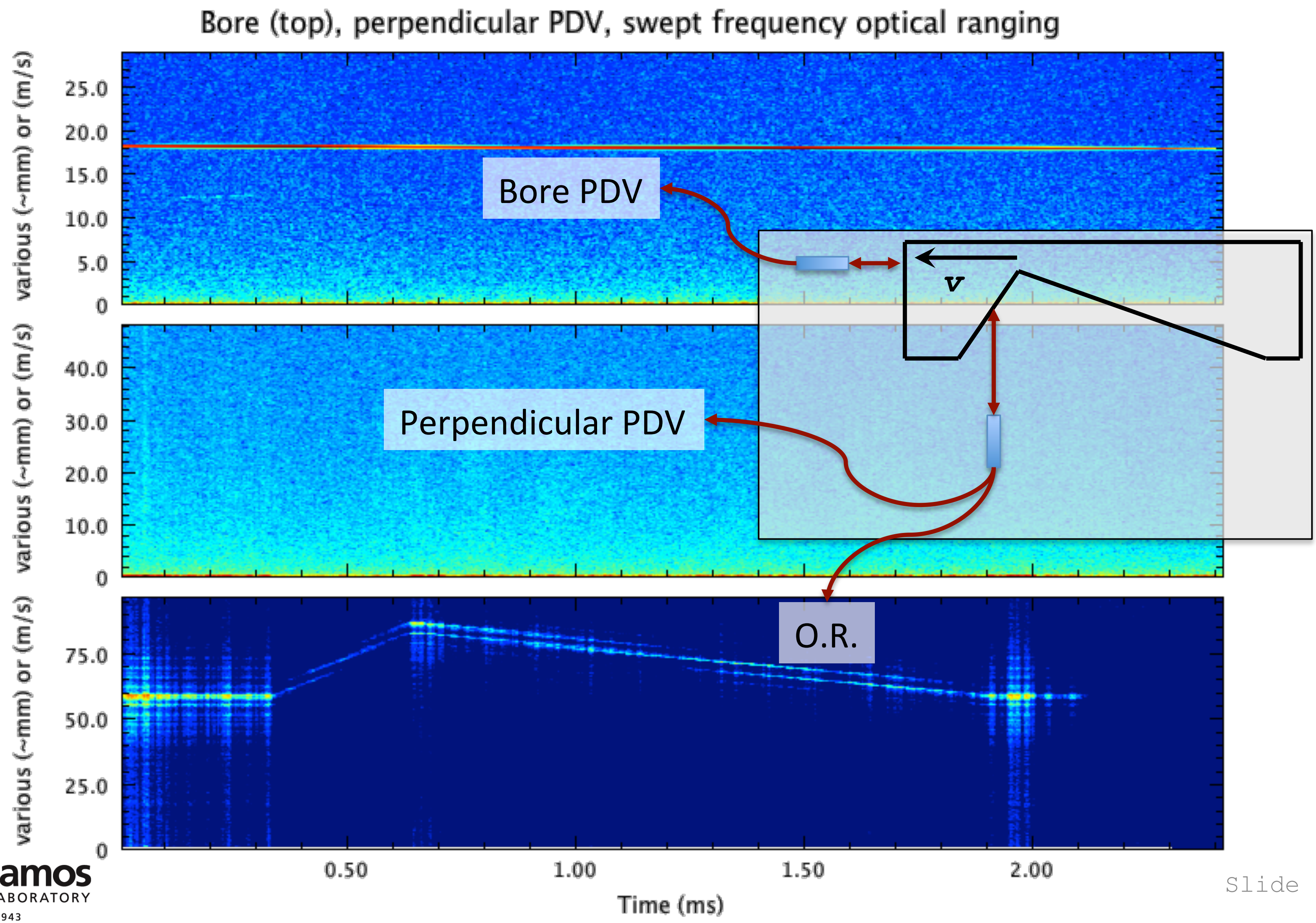
Optical ranging tracks the material location missed by PDV



Hardware Details – Insight Swept Laser

- For our tests, the 10 mW laser's wavelength swept over 1530-1550 nm (capable of larger sweeps, on the order of 100-200 nm)
  - There is a tradeoff between wavelength range, sweep rate, and the density at which the wavelength range is sampled
- Each complete sweep corresponds to a single position measurement
  - These wavelength sweeps took place at a rep rate of 138.50 kHz, generating a position measurement every 7.2 µs
  - 2888 sample points per wavelength sweep (6.9 pm per point, over 20 nm), used to compare the laser's wavelength to a NIST traceable gas reference cell
    - We sampled the optical signal at 50 Gigasamples/sec, compared to the laser's 400 MHZ internal clock, so we measured the interferometer response between these traceable points

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Summary: 2 techniques have passed proof tests, 3rd promising simulations

- The amplitude modulation approach of Younk will coexist with PDV and appears to have the required resolution. The difficulties inherent in phase measurements may be offset by averaging ~100 cycles per measurement.
- Moro's frequency swept approach coexists with PDV and is a frequency measurement rather than phase. The sweep takes 5 µs, which probably needs to be shortened substantially to avoid blur. Our colleagues at NSTec are working on this approach.
- The amplitude-modulation beat-frequency approach proposed by Knierim promises continuous measurement that is frequency based. Tests on this are still needed.
- All of these techniques appear compatible with integration into PDV or MPDV systems with minimal perturbation.

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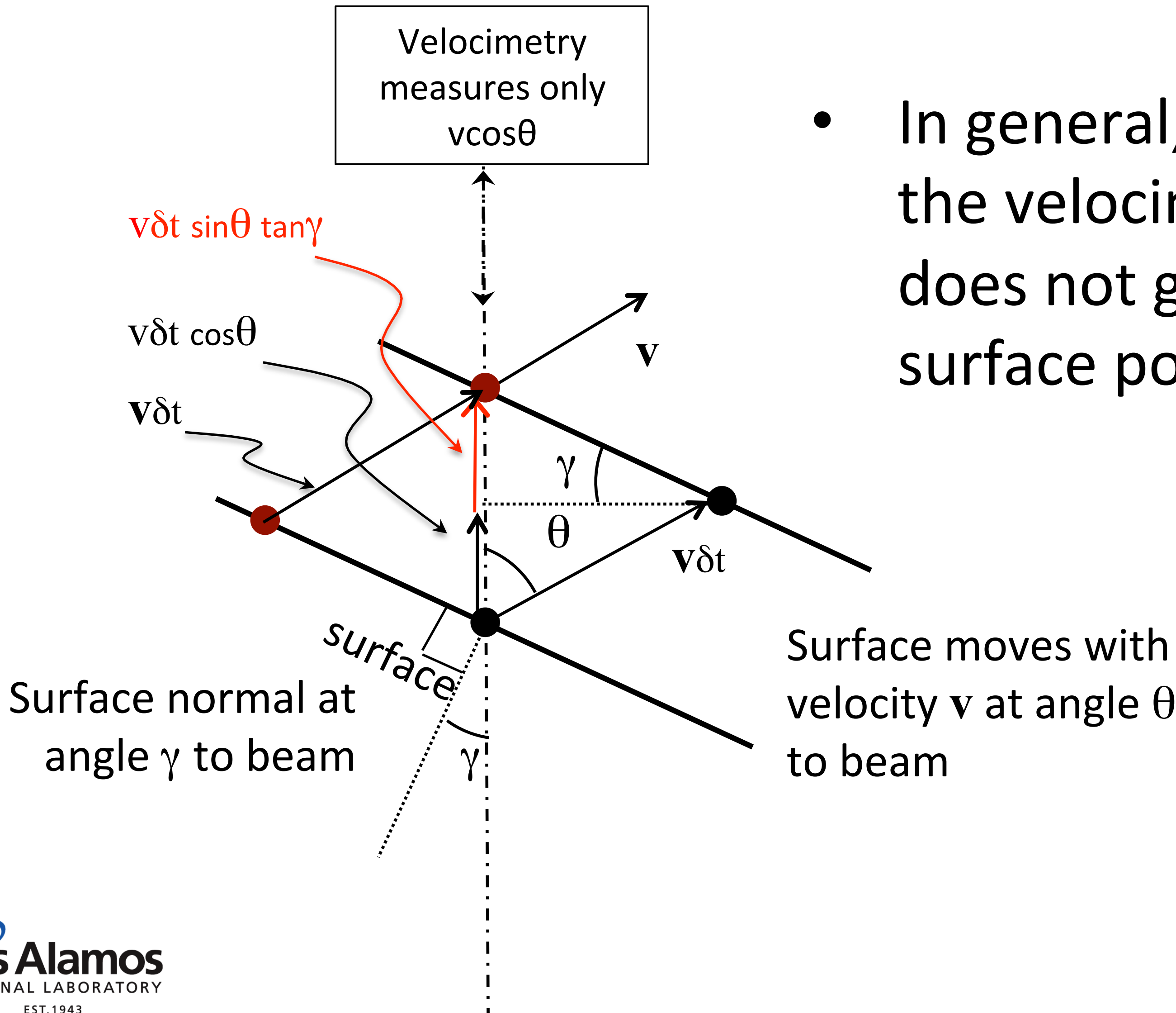
Backups

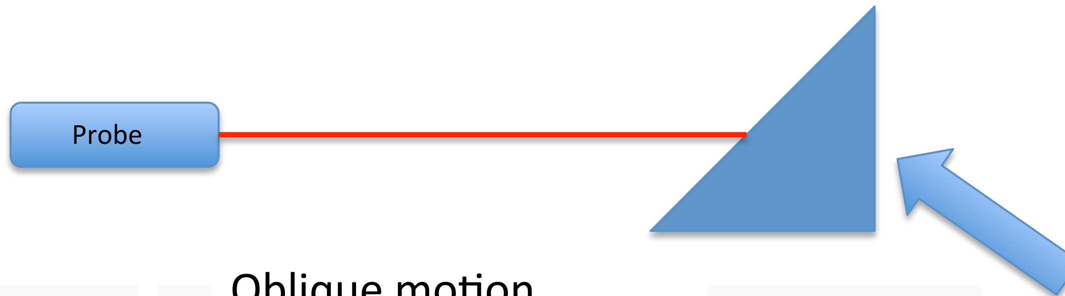
Obliquely moving wedge



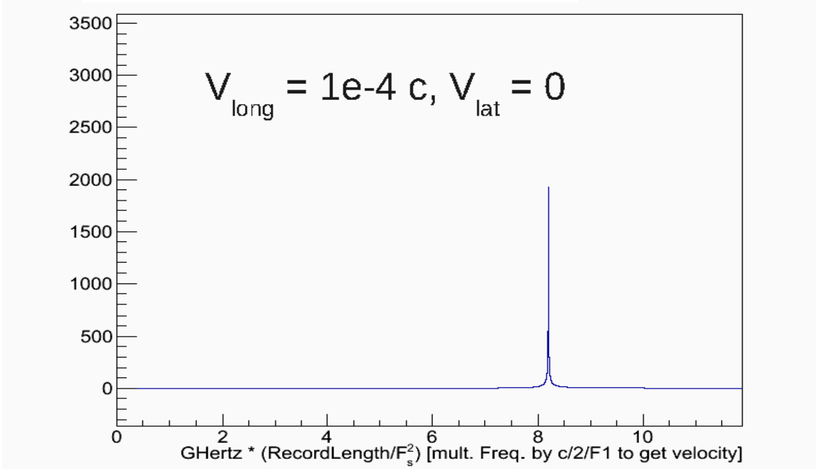
- In general, integrating the velocimetry signal does not give the surface position

Simulation…

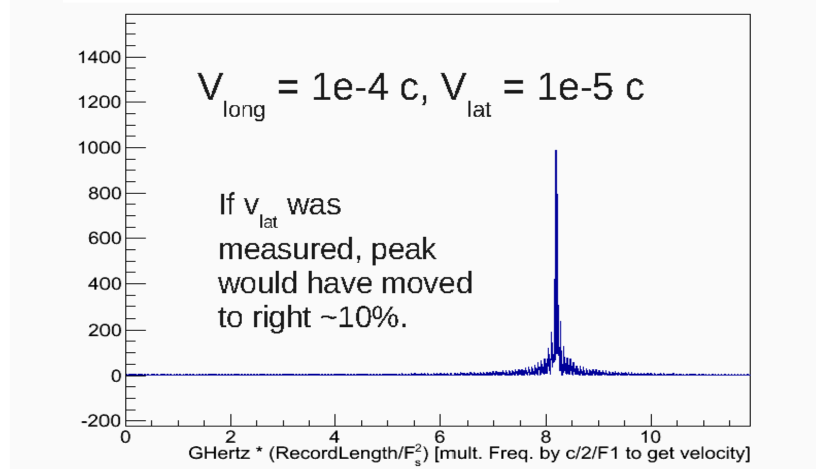
Simulation by Younk: Integral of velocimetry signal does not give the surface position.



Transverse motion



Oblique motion



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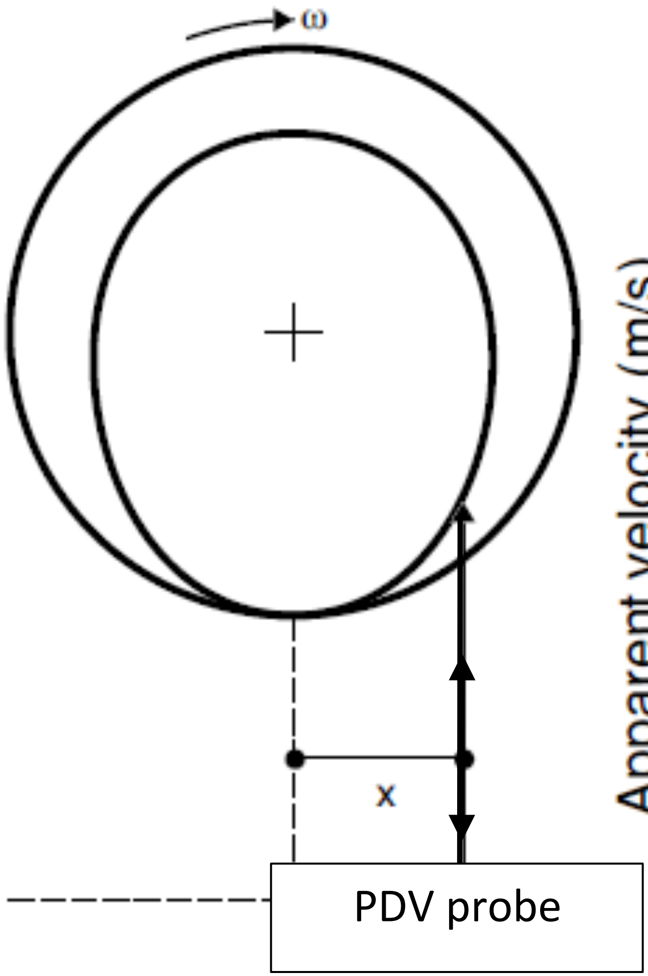
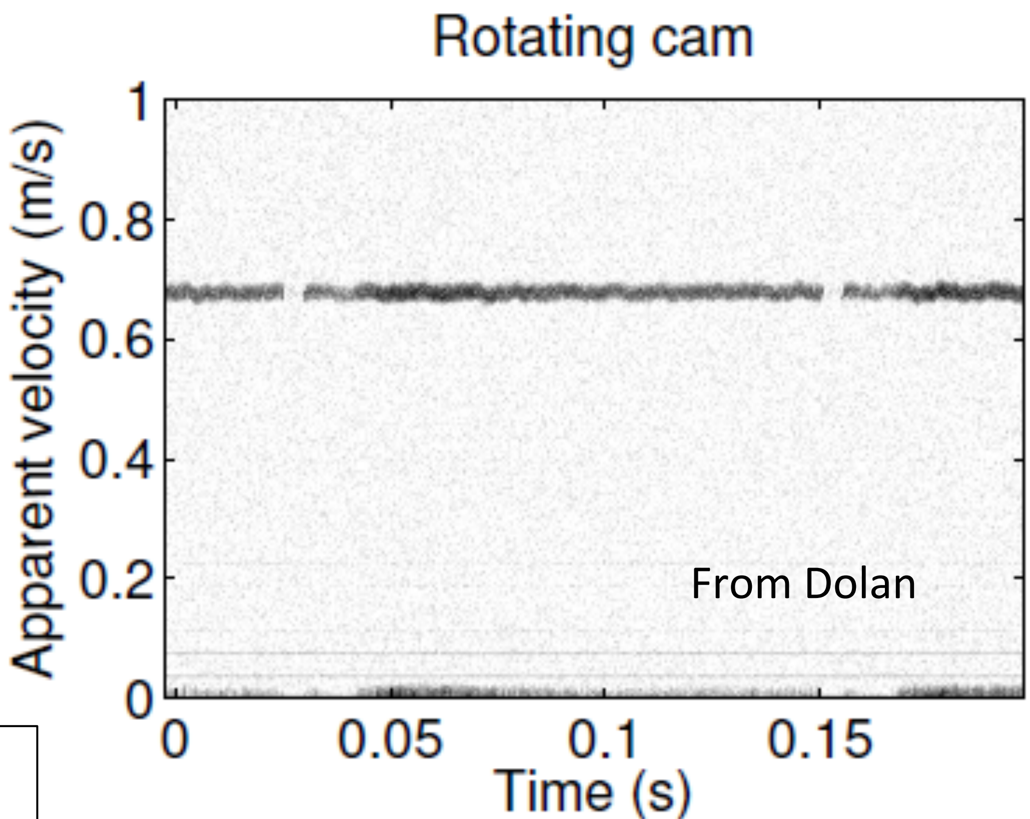
Experiments…





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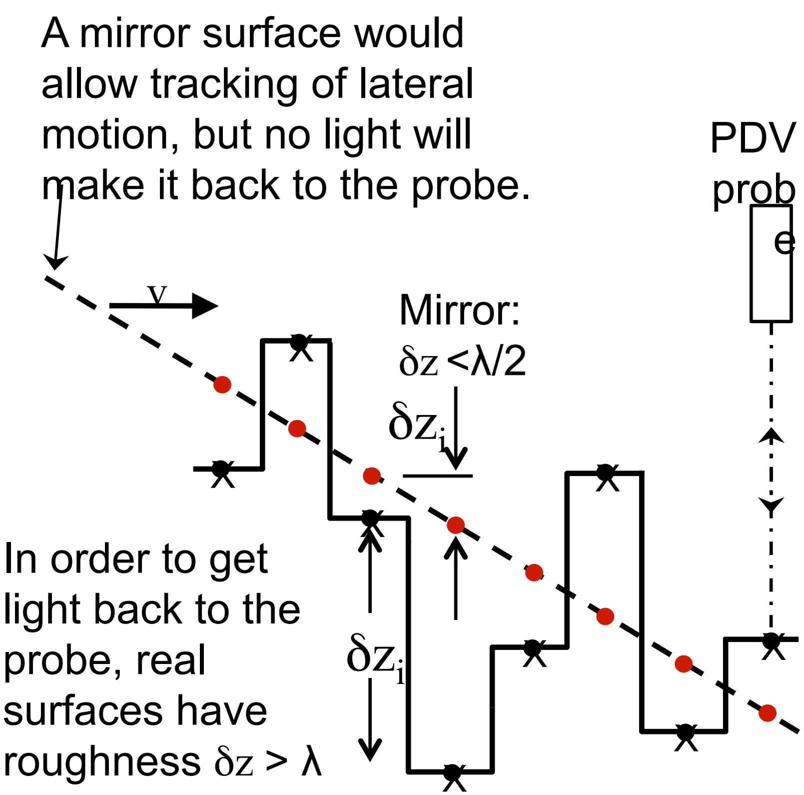
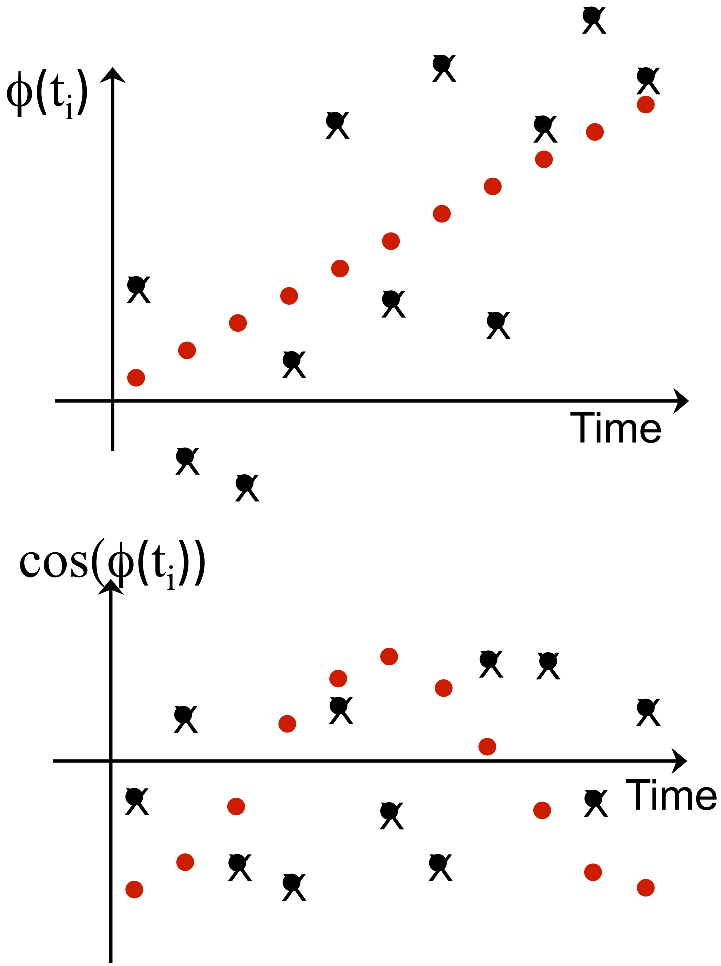
Framed slightly differently

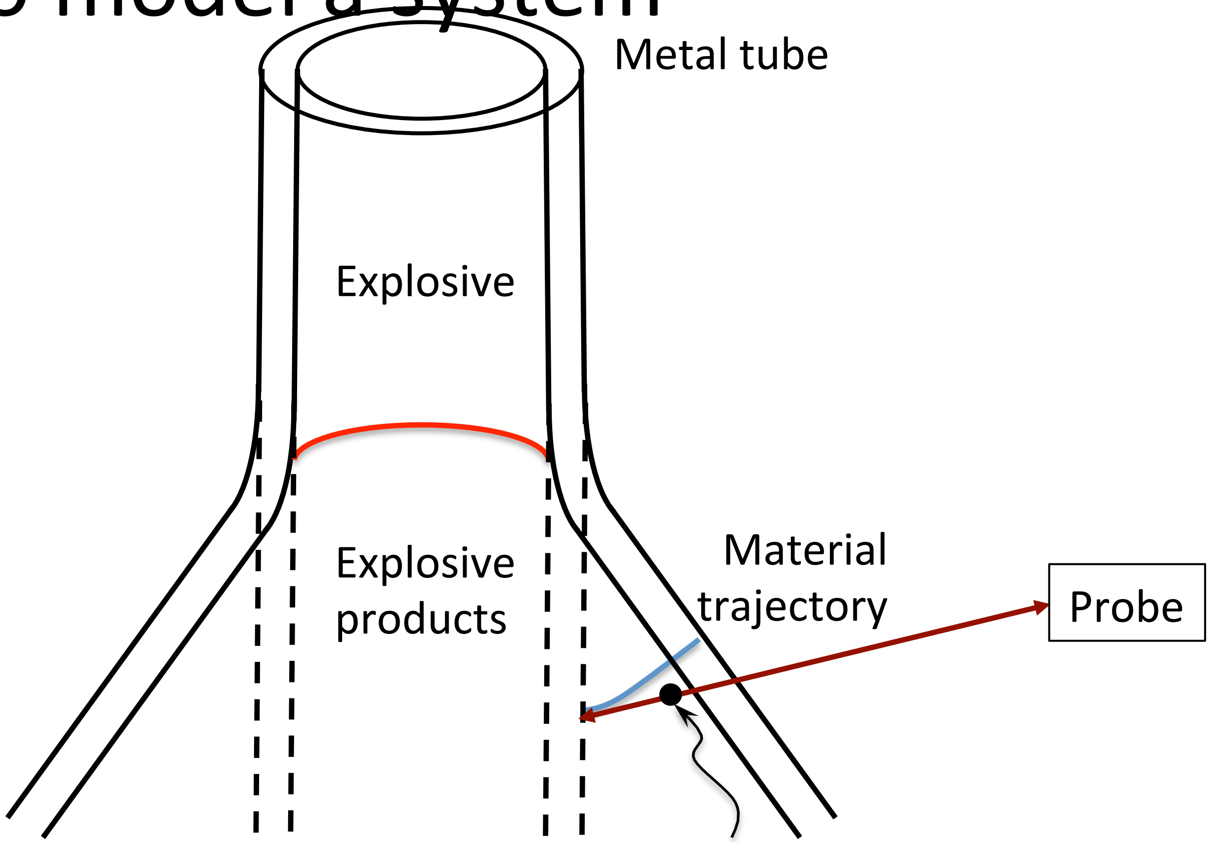
PDV Signal ~ $\cos(\phi_{target}(t))$;





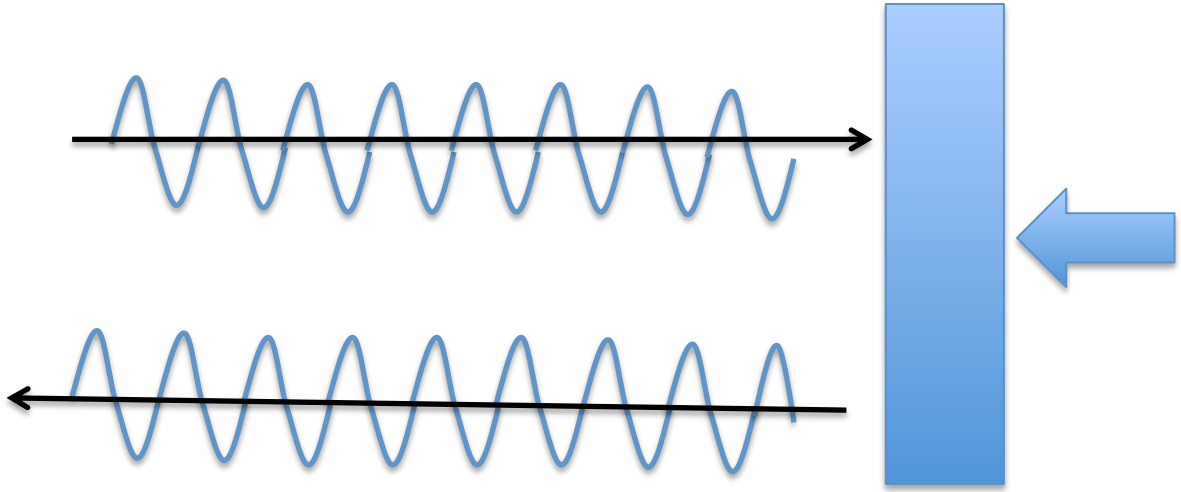
We need to know the location of the material to model a system

- Integrating the velocity measured by the velocimetry method will predict a smaller radius than is in fact present, because some of the radial motion arises from the tilted surface moving axially.



The Optical Ranging Principle

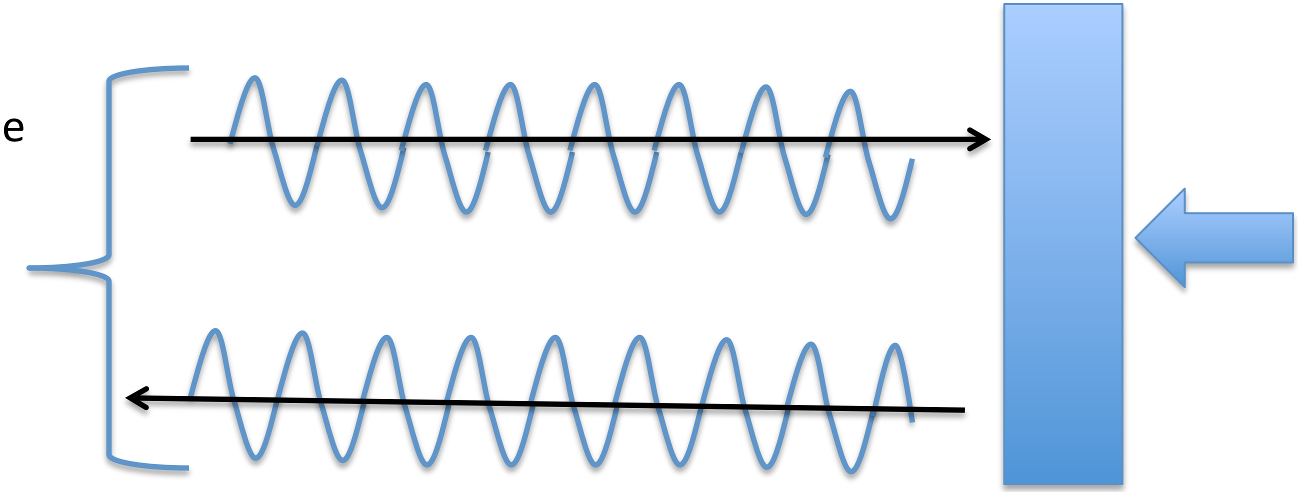
- The phase difference between the send and return **THz carriers** is scrambled by the surface roughness.
- But the phase difference between the send and return **GHz signals** tracks surface position.



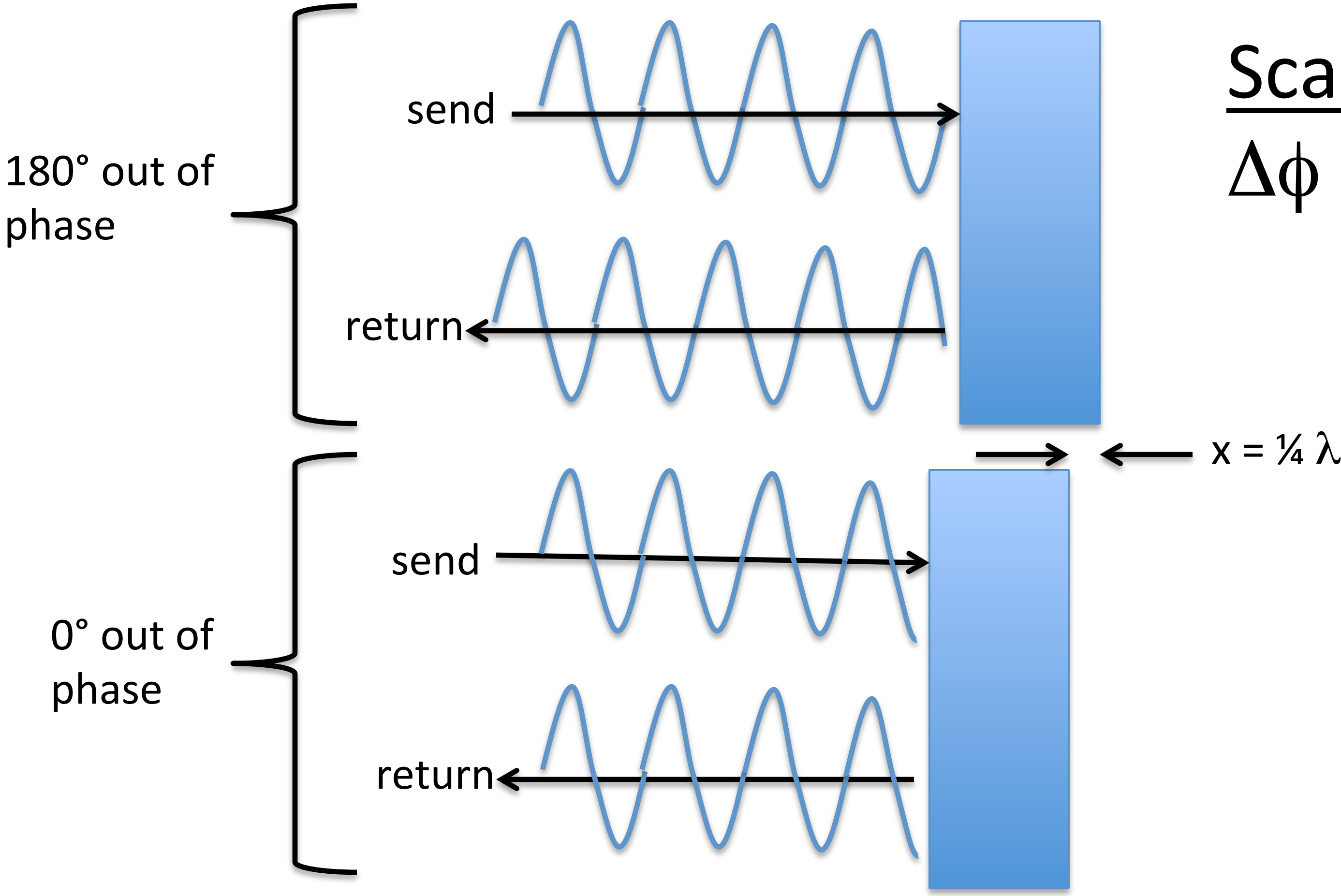
Measuring a phase difference…

- …is different from measuring a frequency difference.
- In the current example, if we let the send and return signals heterodyne, the beat freq. would be ~7 kHz for a 1 km/s approach.

FYI: Combining these raw signals and measuring the beat freq. is a poor measurement of velocity.



Optical Ranging Rules

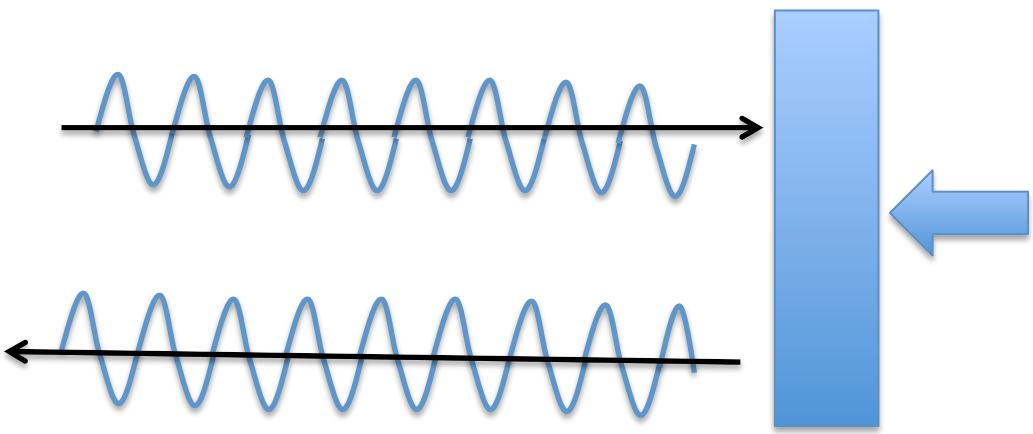


Scale Rule:

$\Delta\phi = 4\pi\, x/\lambda$

Complementarity

- Optical Ranging measures the position of one surface (i.e., the dominate reflecting surface in the beam path).
- Velocimetry can measure multiple velocities or/and the bulk velocity of a cloud of particles.



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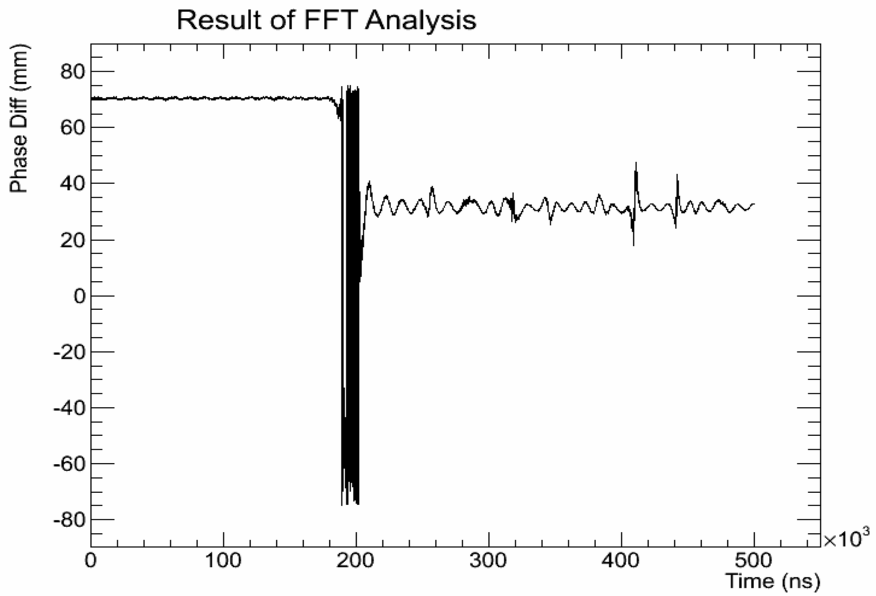
Proof-of-Concept: Results

- 100 kHz wiggle may be due to phase delays in the electronics…



Points

- Proof-of-Concept successful.
- We believe we understand the 100 kHz wiggle. It is straightforward to remove.
- Currently we are at ~0.2 mm resolution and ~10 MHz bandwidth when the signal is reasonably strong.
- This early success is promising.

Variants: Creating the AM modulation

- The AM signal can be made in different ways…
  - Combining two highly stable lasers. Their freq. difference is the AM freq.
  - FM modulating a laser beam and then recombining it with an un-modulated beam.
  - The recombining could be done before or after the beam is sent to the target.
- Each method may have certain advantages…. we are investigating.

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Other Variants

- The phase comparison can be made digitally or with analog circuitry.
- Doppler-shifted Velocimetry and Optical Ranging can co-exist on the same probe.
  - This is of particular interest because of their aforementioned complementarity.
  - But there may be a cost to pay….
  - We may have to double the laser power to maintain the fidelity in PDV.

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