Encoding Velocity in a Photograph

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LA-UR-18-23812

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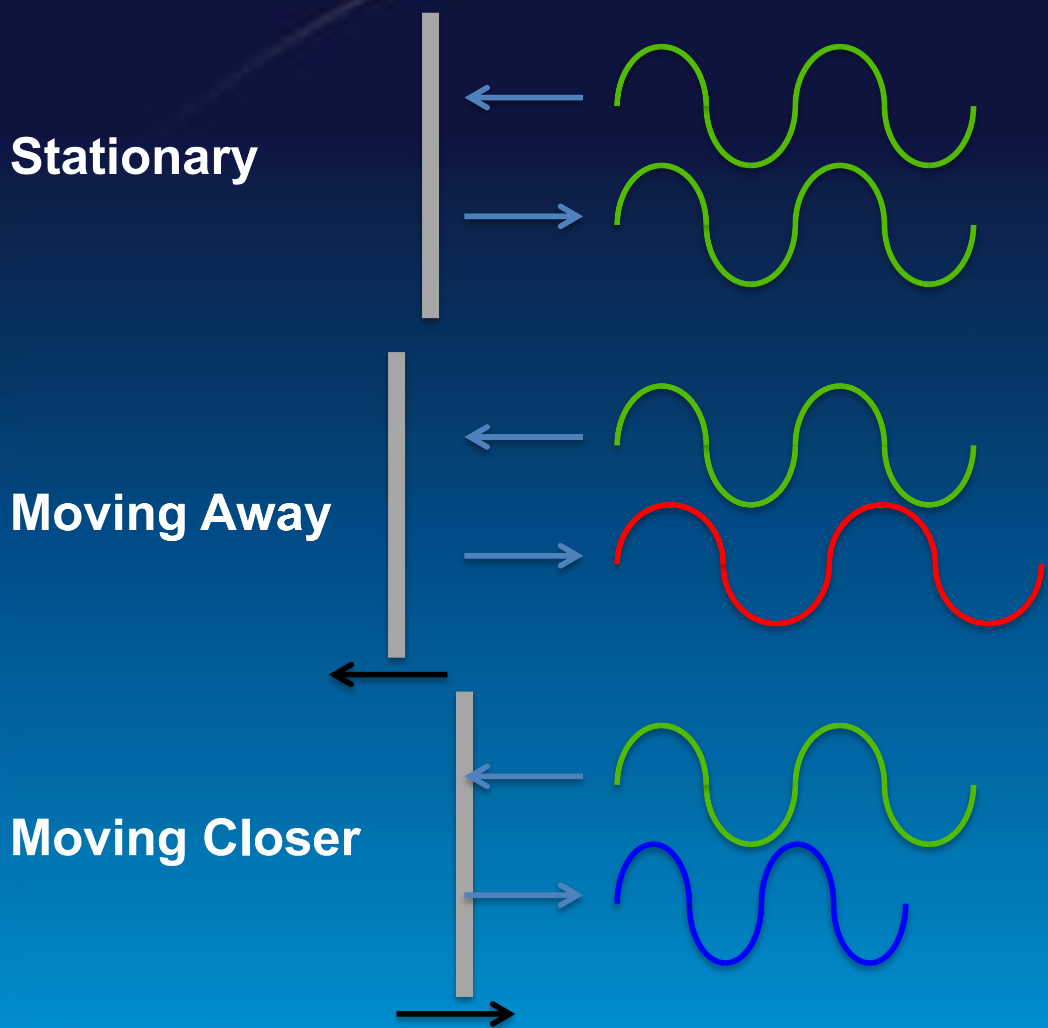
PDV Workshop 2018
May 15-17, 2018
Santa Fe, NM

Velocimetry

- Clearly for dynamic events, knowing the velocity is a very useful measurement.
- PDV or VISAR allow the velocity at a point to be measured with relative ease.
- With enough time and money, up to 256 points can be tracked by PDV
- Line VISAR allows the velocity along a line to be measured (1D). This is not trivial, but can and has been done.

- What if you want to know the whole field velocity of a surface (2D)?
  - **How would you do this? Space out 256 individual probes in an array to form a 16 x 16 pixel image? Not very high resolution. ☹**
  - **What is needed is a spatially continuous imaging method. ☺**

A Doppler Cartoon



- Homodyne PDV is really just a Michelson interferometer, however, another way to visualize it is to note that the reflected frequency of an electromagnetic wave reflecting from a moving object is altered.
- That is, the light reflected from a green car becomes more blue as it drives towards you and more red as it moves away. Obviously the effect is very small since we humans cannot perceive the difference.

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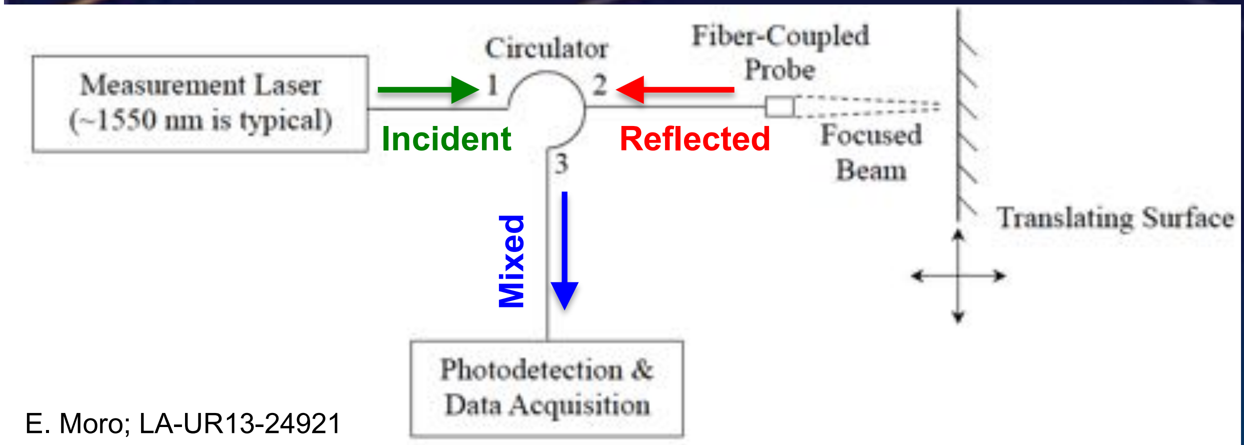
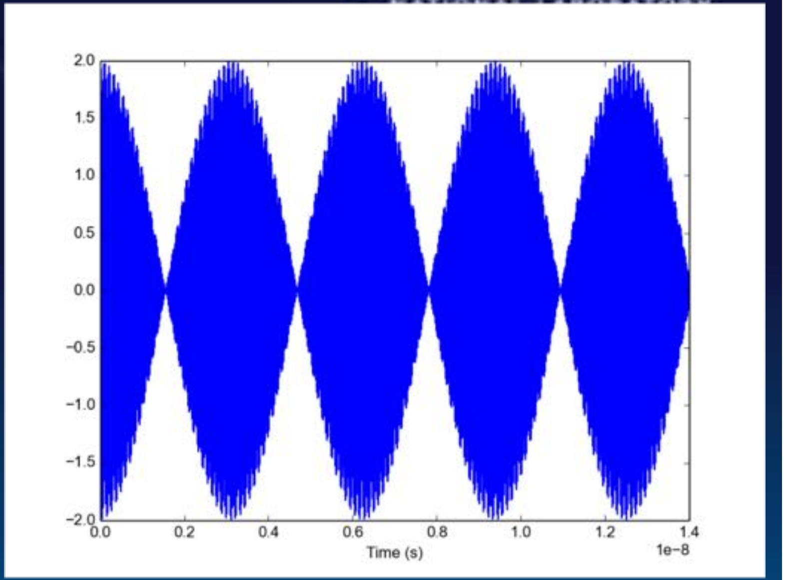
Doppler Velocimetry



E. Moro; LA-UR13-24921



$$f_{observed} = f_{source}\sqrt{\frac{1+v/c}{1-v/c}}$$

- Detection accomplished by interference of reference (stationary) light w/ Doppler-shifted, reflected light resulting in beating on the order of GHz freq.→ "easily" detected w/ simple photodiode & high-speed (expensive) oscilloscope. → velocity = **Frequency modulation**

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Another Way?

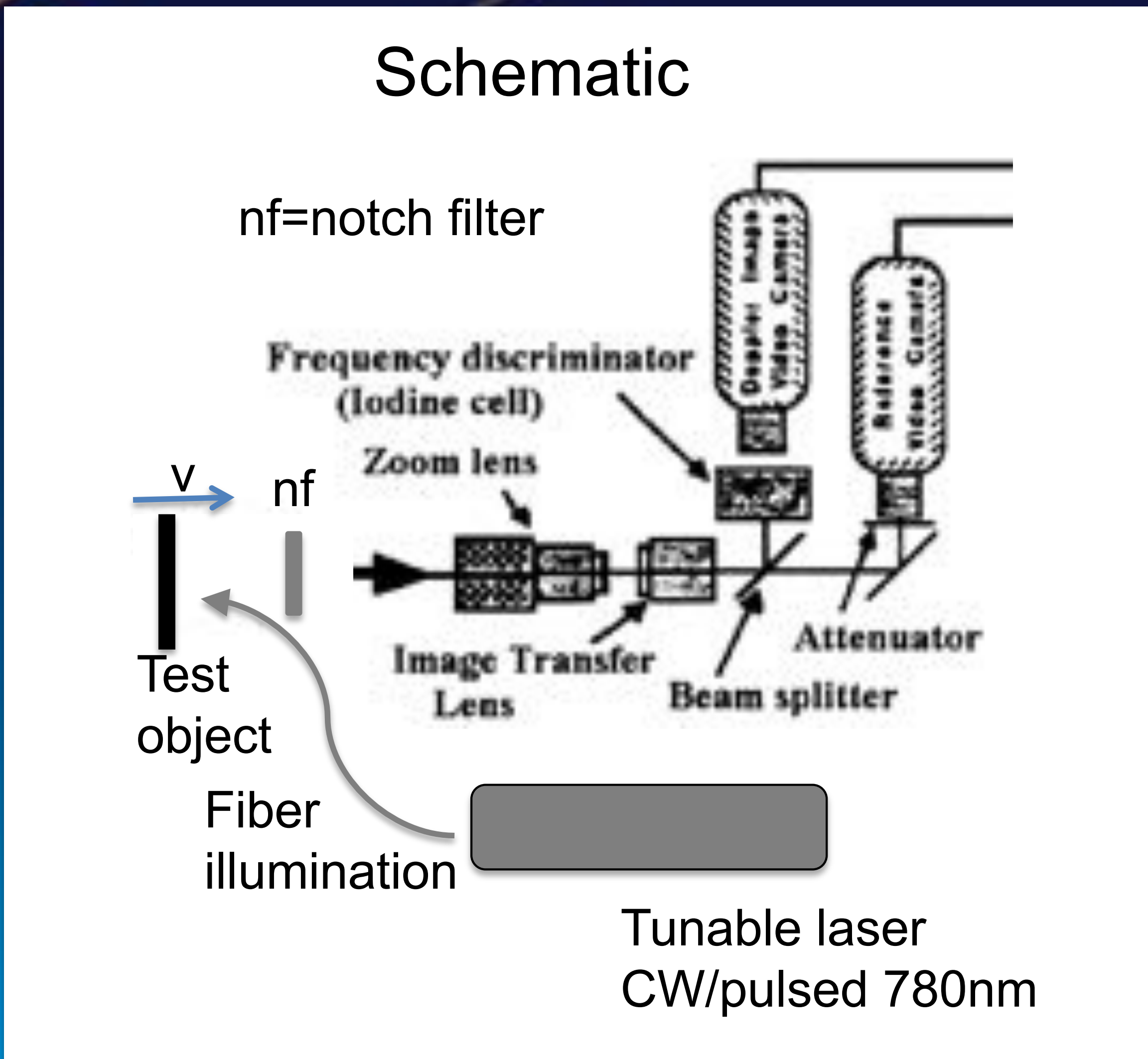
- But what if we could photograph that frequency change?
  - i.e. what if intensity on a camera corresponded to the velocity of the object, not its color?
- Put another way, what if the intensity of the light photographed was just a function of the velocity component normal to the photographic plane?
  - Velocity = intensity modulation

Doppler Global Velocimetry (DGV)

- Known in the literature by several names:
  Doppler Global Velocimetry (DGV)
  Global Doppler Velocimetry (GDV)
  Planar Doppler Velocimetry (the original “PDV”)
  Filtered Planar Velocimetry (FPV)
  Filtered Rayleigh Scattering (FRS) Velocimetry

- The basic principle involves a narrow laser frequency (usually in the visible) being tuned to an absorption line of an element (iodine, cesium, rubidium etc.) in a translucent cell to act as a very sharp frequency filter.
- Then the Doppler shift from a test object changes the local absorption on the elemental line and hence intensity exiting the filter cell. Typically it is arranged for faster objects to appear brighter.
- A second split beam path is made where the returned light is not line filtered. This normalizes for changes in surface reflectivity, laser pulse-to-pulse intensity variation etc.

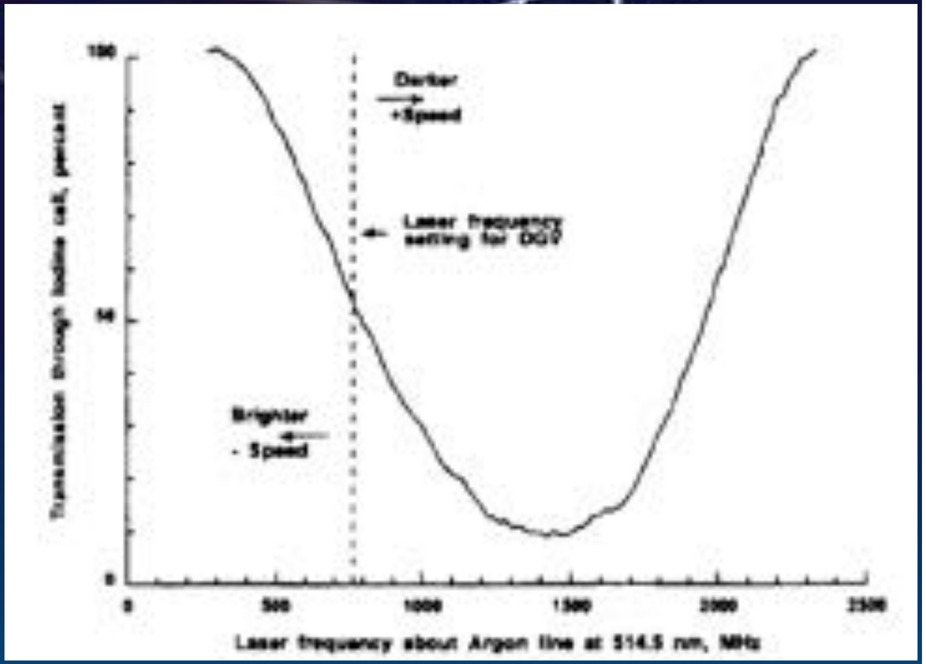
The Principle

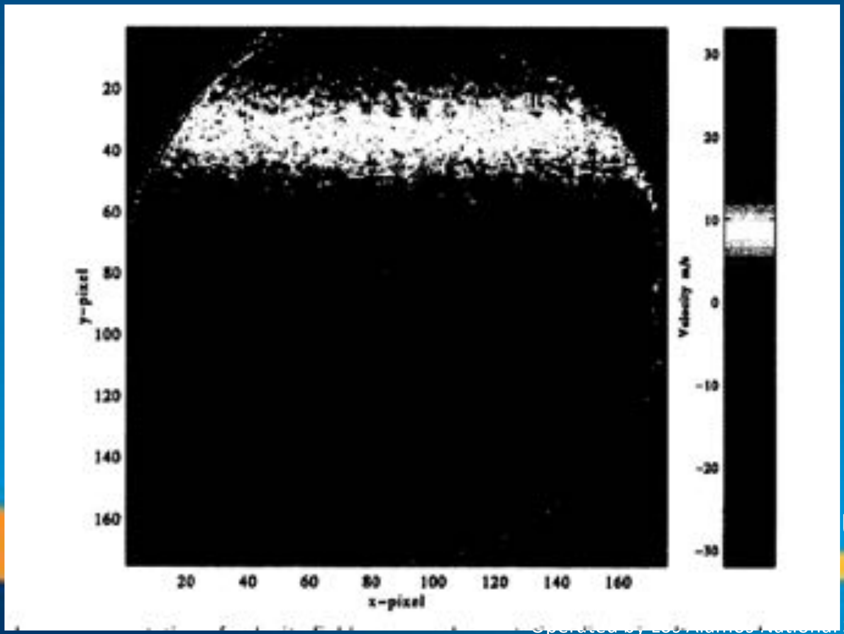


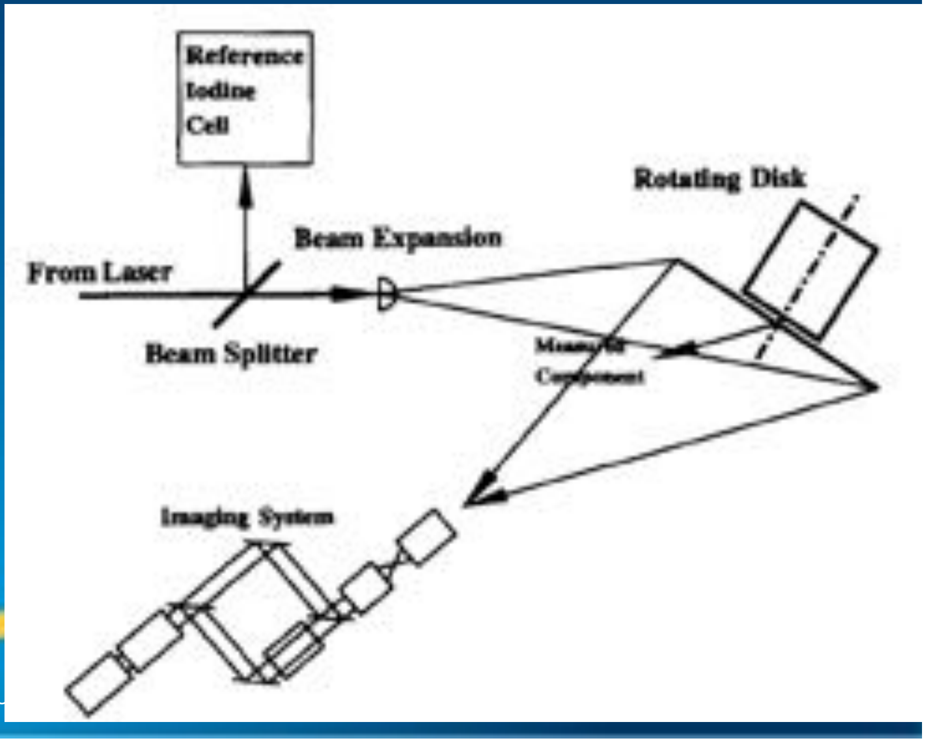
- Light from a tunable 780nm laser falls on a reflective target surface.
- Reflected light goes through a notch filter to reject any spurious light.
- Imaging optics split the laser light into two paths.
- Path A goes through a very sharp atomic absorption filter effectively converting the object velocity to intensity.
- Path B goes through a neutral density filter and to a second camera to allow image normalization for reflectivity changes

Fluid Mechanics Guys Beat Us to It

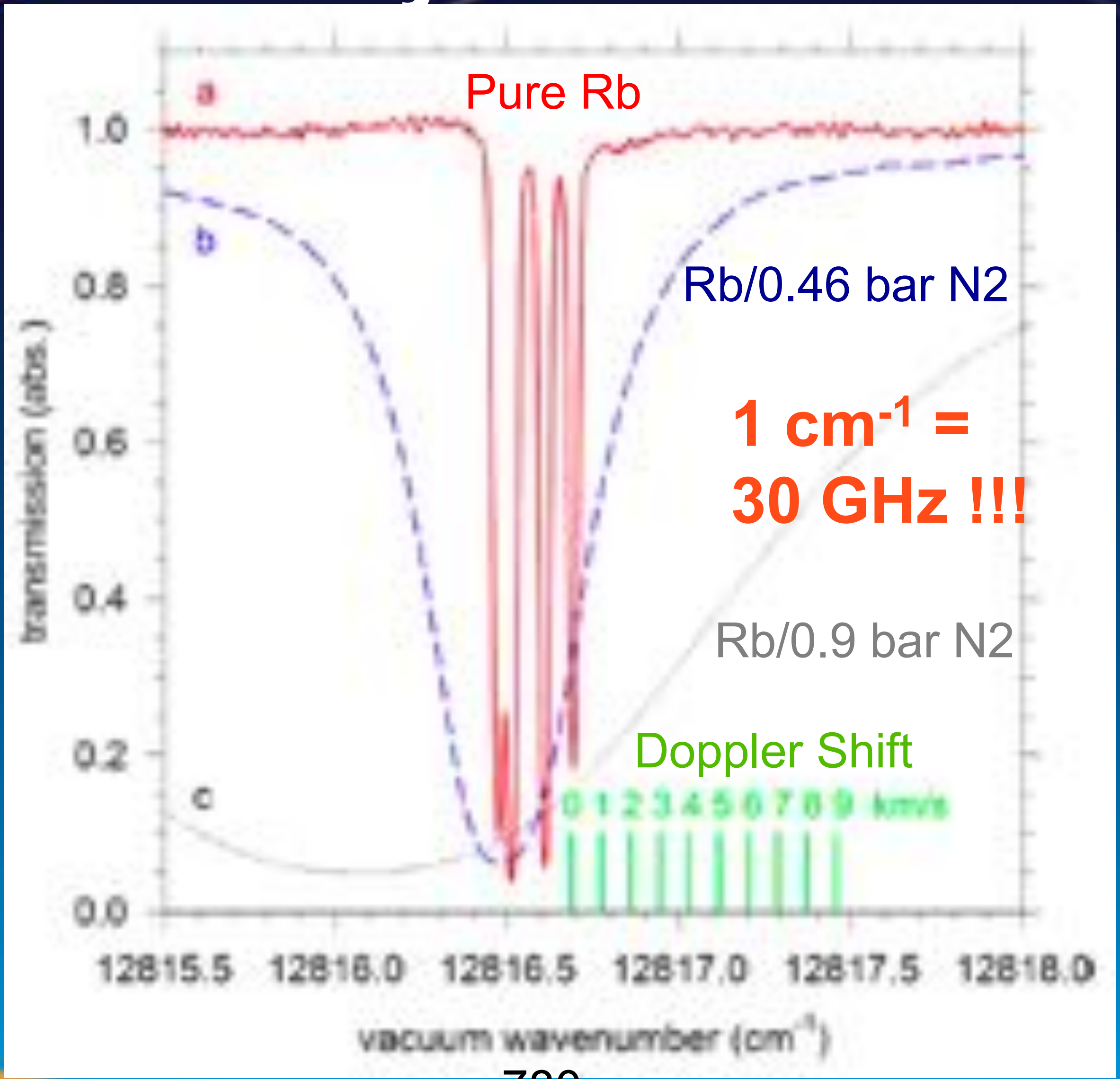
- Using a pressure-broadened iodine cell, Ainsworth *et al*. (1994) showed that it was possible to image a rotating disc and see velocity component in image.
- Requires very frequency-stable illumination laser source (1 m/s = Δf = 2MHz) and to be on “linear portion” of absorption curve to assume Beer’s law.
- Width of linear absorption feature limits measureable velocity range. In iodine molecular cell used here, linear region ~ 600 MHz wide = 300 m/s max velocity.







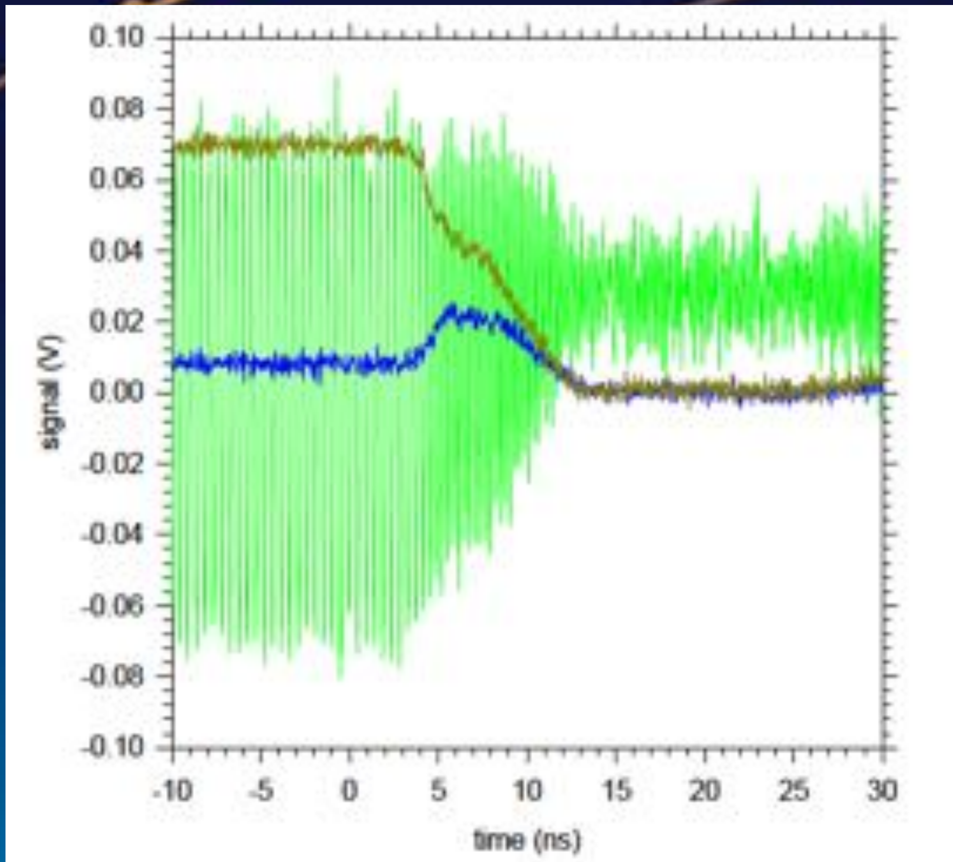
How can we make this useful to Shock Physics? A Better Filter

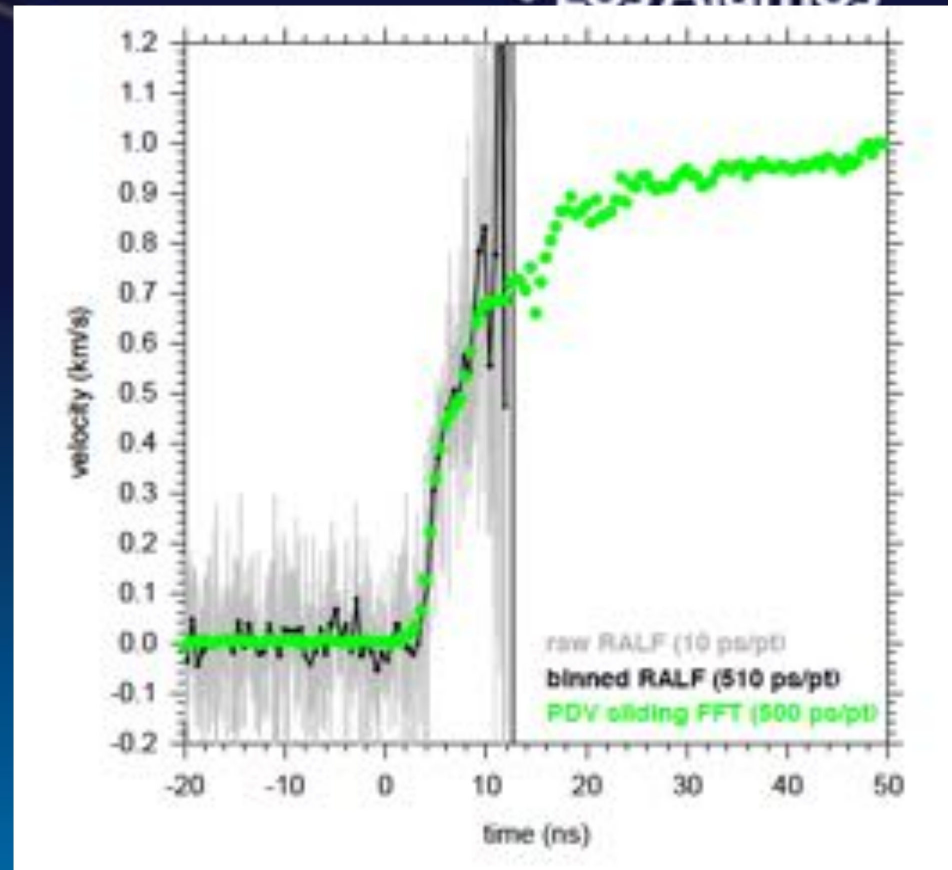


~780nm

- Fajardo *et al*. (2015, 2017) used Rb-cell w/ very sharp atomic absorption bands in red visible freq.
- Bands can be smeared by addition of N_2 to cell.
- Temp. & N_2 pressure affect steepness of band.
- A combination exists that allows light from stationary object to be almost fully absorbed, but a fast moving object to be fully transmitted.
- Desirable combination depends on the expected velocity of the object.
- Better bandwidth ~ 30 GHz
- Pressure-broadening minimizes nonlinear optical effects.

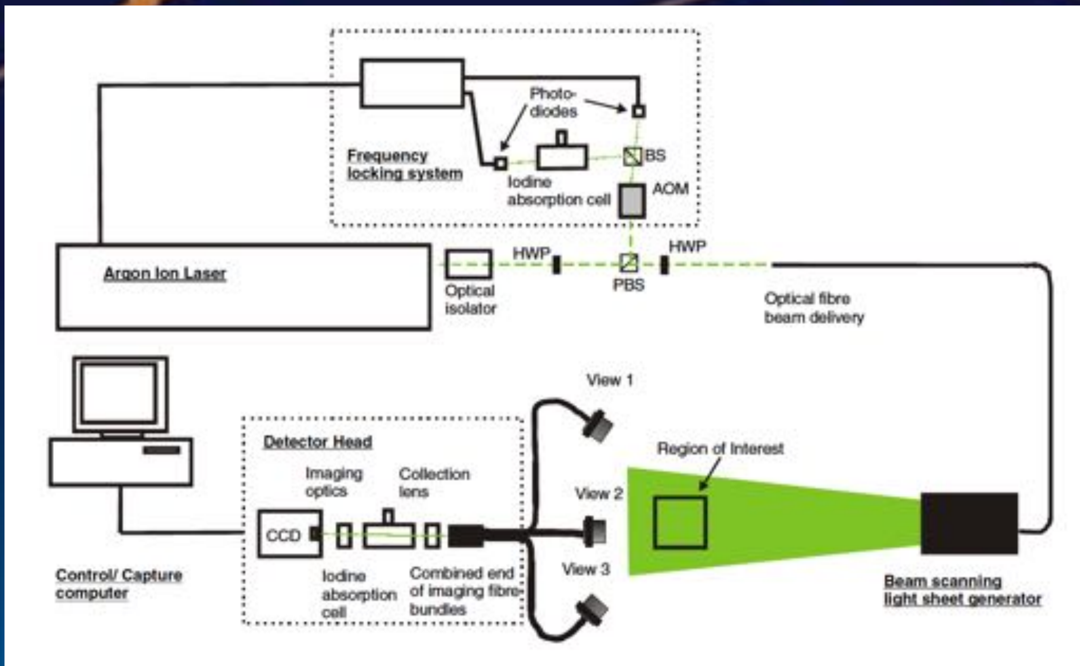
A Better Filter (cont.)



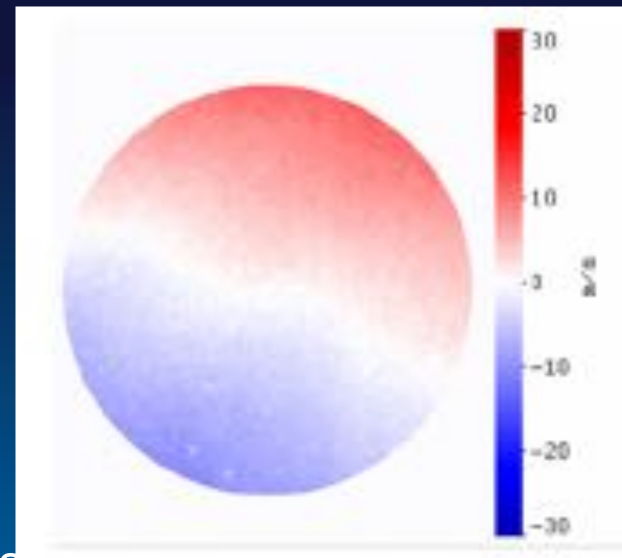


- Here, Fajardo *et al.* show comparison between PDV (green) and RALF (blue). Ref. (gold). Target = Laser-driven Al flyer
- SNR isn't fantastic but agrees with PDV when data is binned and over velocity ranges that are useful to the shock physicist.

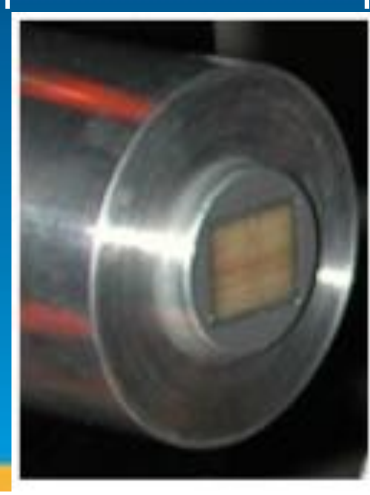
Free Optics are nice in the lab…

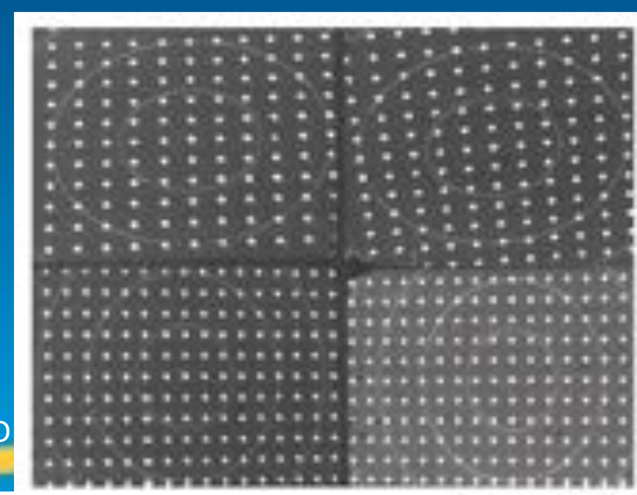


- Charrett *et al*. (2006) used coherent optical imaging bundles to image rotating disc using PGV.



Each channel has 600x500 fibres
that are 8μm in diameter and positioned at 10μm centres.





100mm x 100mm field

Examples of coherent optical imaging bundles

Practicalities

- Sensitivity/resolution improved by two factors:
  - Brightness of source
  - Interframe rate and exposure of camera.
  - Spatial resolution of camera.
- The use of a pulsed laser helps stop motion blur and get sufficient intensity for dynamic events. May have to watch for absorption cell nonlinearities at high power.
  - Pressure-broadening helps.
- Up to 250 mW/cm^2 CW good so far in Rb cell. But pulsed lasers will get us to kW/cm^2. We'll have to see whether this will be ok.
- Multimode optical fibers are great for this application.
- The use of coherent optical bundles would separate the dynamic/violent test from the expensive diagnostic.
- Clever optics would allow the LHS of the frame to be the moving surface and the RHS to be the reference. This saves an expensive high-speed camera.
- For example, Kirana high-speed camera at 5 million FPS and 924 x 768 pixels; 180 frames;
  - 200 ns interframe time; 36 us shortest total record length.

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A Few Potential Applications

- Shock breakout on a polycrystalline surface. Since the wave speeds along individual crystallographic axis vary somewhat, a flat-fronted shock is not really flat in a polycrystalline solid since the time of arrival at an observation free surface will have variance both from the wave speed differences and internal wave reflections and interactions.
- Instability growth and ejecta at a shocked surface. A shock breaking out at a material interface will often have instabilities seeded by surface imperfections and this can lead to ejecta. It would be useful to track the velocity buildup of that process over an area rather than a point or line.
- Heterogeneous breakout of a detonation in a solid explosive. This is a more challenging problem owing to the short timescales.

Acknowledgements

- Philip Rae
- Hiroshi Komine for initially inventing the concept

Coherent optical transients observed in rubidium atomic line filtered Doppler velocimetry experiments

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A new approach to flow-field measurement—A view of Doppler global velocimetry techniques

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Single camera 3D planar Doppler velocity measurements using imaging fibre bundles

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