LA-UR-07-0940

Approved for public release;
distribution is unlimited.

Title: SURVEY OF OPTICAL VELOCIMETRY EXPERIMENTS – APPLICATIONS OF PDV, A HETERODYNE VELOCIMETER

Author(s): David B. Holtkamp, P-22

Intended for: 2006 International Conference on Megagauss Magnetic Field Generation, November 5-10, 2006, Santa Fe, New Mexico

Los Alamos
NATIONAL LABORATORY
EST. 1943

SURVEY OF OPTICAL VELOCIMETRY EXPERIMENTS – APPLICATIONS OF PDV, A HETERODYNE VELOCIMETER

David B. Holtkamp, Los Alamos National Laboratory, Los Alamos, NM, USA

ABSTRACT
Optical velocimetry has been an important experimental diagnostic for many experiments. Recent improvements to heterodyne techniques have resulted in compact, inexpensive and high performance velocimetry measurement systems. We report on developments and improvements in this area and illustrate the performance of Photon Doppler Velocimetry (PDV) by showing several experimental examples.

INTRODUCTION
Laser based velocimetry (VISAR, Fabry-Perot, etc) has long been a vitally important diagnostic in many shock and non-shock experiments. Recent developments in telecommunications technologies (fibers, detectors, digitizers, etc) have enabled our colleagues at LLNL[1] to develop a compact, inexpensive and robust method of laser based velocimetry that is a significant advance of the state of the art. This method – Photon Doppler Velocimetry (PDV) – is a simple, relatively inexpensive approach to measure surface velocities between a few mm/s up to 14 km/s or higher. There are several aspects of PDV that make it a favored approach to use in optical velocimetry. Because it uses a single 9/125 micron optical fiber for both transmit and receive, optical probes can be quite small and high performance. The system uses 1550 nm CW fiber lasers which are very nearly eye-safe under normal use. Most importantly, because the velocity measurement is embedded as a frequency in a time domain signal, powerful DSP methods can extract even very weak signals with high accuracy. This means that under difficult experimental conditions (degraded surfaces, ejecta, etc) one can obtain reliable measurements when other approaches would likely fail. Recently, Weng et al.[2] published a description of an all fiber optical velocimeter using many similar concepts. Weng also shows the flexibility of including multiphase detection of these signals to determine the direction as well as high temporal resolution of the velocity.

We have developed and improved several systems at Los Alamos based on the LLNL approach and have found that these systems are much less expensive and easier to field that other optical velocimetry (e.g. VISAR, Fabry-Perot) techniques. We present a survey of experimental results obtained with these systems and outline the variety of experimental conditions and optical probes used to obtain them.

DESCRIPTION OF OPTICAL VELOCIMETER SYSTEM
The authors of references 1 and 2 provide comprehensive descriptions of how these systems are constructed and how they work. For the purposes of this article, I would like to describe how a PDV works in a slightly different way.

One way of thinking about a PDV is as a very fast Michelson interferometer where the moving surface to be studied is the moveable leg, and the unshifted reference light is the other fixed leg of the interferometer. Figure 1 shows a simplified layout of a Michelson interferometer and a diagram of a simplified PDV system. The reference leg of the Michelson interferometer is produced by a reflection from the fixed mirror, while the moving mirror produces a changing path length for the other leg. These two phases recombine on the detector (green leg) to produce interference fringes that track the motion of the moving mirror where the displacement (Δx) is proportional to the number of fringes (n) and the wavelength of the laser (λ) using the expression $\Delta x = n \cdot \lambda/2$.

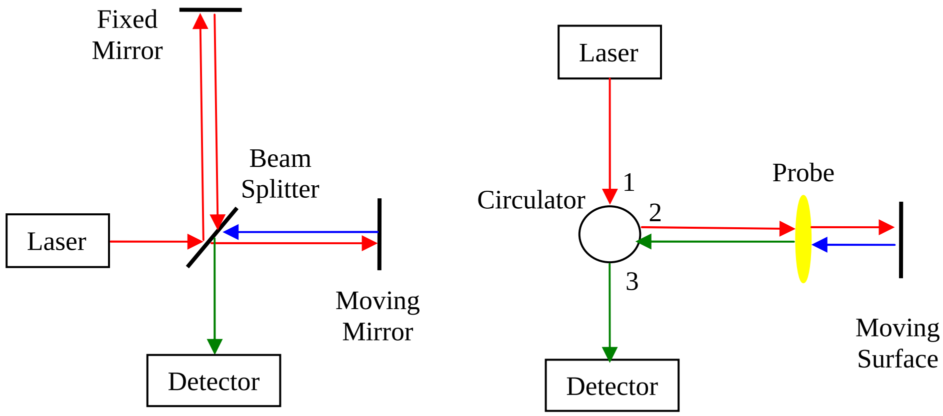

Figure 1: Michelson interferometer (left) and simplified schematic diagram of PDV (right) showing the unshifted (reference) light in red, the Doppler shifted light in blue, and the combined unshifted and shifted light in green.

Instead of using a beam splitter like the Michelson interferometer, the PDV uses a component developed in the telecommunications industry called a fiber optic circulator.[3] The circulator performs as an optical directional coupler for the input light on fiber port 1. This light exits on port 2 and is transported to an optical probe of some sort (yellow). The incident light is reflected from the moving surface (blue) to reenter the same fiber and reenters port 2 where it is directed in the circulator out port 3. One method of introducing the proper amount of unshifted (reference) light is by specifying a back reflection at the probe (-20 to -30 dB, depending on the application). Thus the required reference light travels back in the same fiber as the Doppler shifted light (blue) to produce the mixed light (green) that beats at the detector.

One can track the distance moved by the surface illuminated by the PDV in a perfectly analogous manner to the Michelson interferometer by counting fringes (i.e. $\Delta x = n \cdot \lambda/2$). In our case, we are interested in the velocity (V) of the moving surface which is given by the expression $V = F \cdot \lambda/2$, where F is the fringe frequency (in Hz). In our PDV systems, we use a 1550 nm fiber laser and the conversion from frequency to velocity is such that V(km/s) = 0.775 · F(GHz). Thus, a velocity of 1 km/s corresponds to a recorded frequency of ~1.29 GHz.

A single 2 to 5W laser can be used with one or more fused fiber couplers (i.e. “splitters”) to produce light for several PDV points. Depending on the experimental surface preparation, probe efficiency, etc, a single PDV channel may require an incident optical power of 10’s of mW to 100’s of mW. In either event, a several W laser can readily provide enough power for 4-8 points (or more).

Strand *et al.*[1] describes the PDV in terms of frequency heterodyning between the Doppler shifted light reflected by the moving surface and the unshifted laser light. Weng *et al.*[2] describe their instrument as a Displacement Interferometer System for Any Reflector (DISAR) which is a rather nice acronym. PDV truly has its origins in Laser Doppler Velocimetry from the 1960s.[4] We have chosen to adopt the acronym PDV since the implementation of Strand *et al.*[1] was originally presented with this name in the context of high velocity experiments.

LOS ALAMOS PDV SYSTEMS

We have made design choices analogous to those of Ref 1 on components for our PDV systems.[5] There are many high-performance components available in the telecommunications industry, so the reader can make different (perhaps better) choices depending on their requirements.

Because PDV systems are entirely enclosed in optical fiber, they do not require adjustable optics or other fragile components. Our systems are configured to be easily portable and are moved from experiment to experiment as needed. Figure 2 shows a 12 point installation using equipment mounted in portable wheeled cases.[6] In this case we used two 5 W IPG lasers and three 4-channel detector boxes, that each contain all the splitters, circulators, and power meters used in a PDV system. Typically, the digitizing oscilloscopes are Tektronix units (TDS 6804B). In this case we used two scope channels to provide dual voltage range coverage for each PDV detector channel.

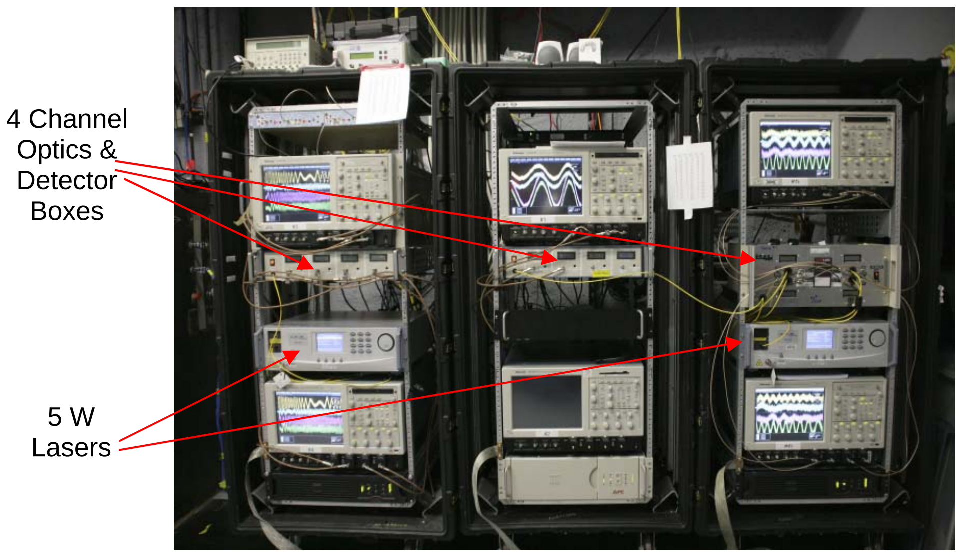

Figure 2: A typical portable installation of 12 PDV channels, using two 5 W fiber lasers, three 4-channel PDV optic/detector boxes, and digitizing oscilloscopes.

The upper limit of velocity measurement in our baseline configuration is nominally determined by the analog bandwidth of the TDS6804B oscilloscopes (8 GHz $\Leftrightarrow$ 6.2 km/s), rather than the detectors or the single mode fiber. With higher bandwidth recording, much higher apparent velocities are possible (see below). In principle, the absolute accuracy of PDV depends only on two well known quantities: (a) the accuracy of the time base of the recording oscilloscope (typically a few ppm); and (b) the wavelength of the laser (typically known to ±0.1 % or better). In practical experiments, there is an inevitable (though favorable) tradeoff between absolute accuracy and time resolution of the inferred velocity.

EXAMPLES OF EXPERIMENTAL RESULTS

One of our first experiments with PDV was to measure the free surface velocity of high explosive driven tin. Figure 3 shows the experimental geometry and the raw digitizer data. First motion of the tin occurs near 3.91 μs and a number of features in the raw data appear between 5 and 6 μs.

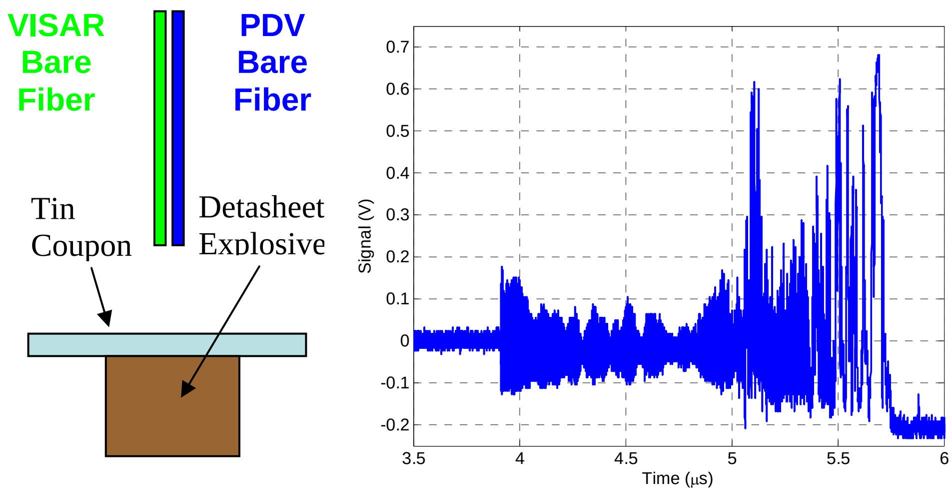

Figure 3: Diagram (left, not to scale) of initial experiment geometry where a bare fiber PDV was mounted alongside a bare fiber VISAR probe with a standoff of ~2 mm. The raw PDV data (right) illustrates several features of heterodyne velocimetry.

Figure 4 is a short time Fourier transform[7] (i.e. Gabor transform) of the data in Figure 3. The colors correspond to the spectral power density (in dB) of the velocity signal in the frequency (i.e. velocity) domain. The start of motion neat 3.9 μs is clearly visible, as is the impact of the tin free surface on the probe near 5.5 μs. The ~2 mm probe standoff is reflected in the integral of the ~1.2 mm/μs velocity for the ~1.6 μs of travel. The faint signals after ~4.5 μs at velocities between 1.2 and ~1.8 km/s are the signature of shock generated ejecta from the tin. As these ejecta begin to strike the probe, their slower velocity signature (which has a large SNR as they bounce off the probe) between 5 and 5.5 μs does not show the direction of motion since this PDV has no directional information. The fiber continues to respond for a few hundred ns after impact (~5.5 μs) until the probe is destroyed.

This data set illustrates how it is possible to detect multiple velocities simultaneously with PDV and clearly distinguish (under favorable conditions) the intact metal free surface, faster moving ejecta, and other features in the data set. It is worth noting that the free surface velocity trace has generally a 30 dB (or more) SNR, corresponding to about 1000:1 contrast (in the frequency domain) – which is quite substantial. The data also shows that this contrast is modulated, sometimes quite strongly, to the extent that the free surface velocity trace almost vanishes entirely. But because the velocity information is encoded in the frequency in the time domain data, once the SNR improves the velocity can be recovered. This results in velocimetry that is very robust and insensitive to even large changes in the surface reflectivity.

The modulations, which are quite apparent in the raw data of Figure 3 (between ~3.9 and 5.5 μs) are likely caused by dynamic speckle in the reflected, Doppler shifted light. These modulations often appear from machined or diffuse surfaces, but are almost entirely absent when the surface is polished to a mirror-like finish. When modulation is observed from mirrored surfaces, the depth and frequency of the modulation are much reduced compared to rough surfaces. However, mirror finishes are more likely to cause large signal variations due to tilt but they do, of course, provide the highest directional reflectivity (and thus highest signal return).

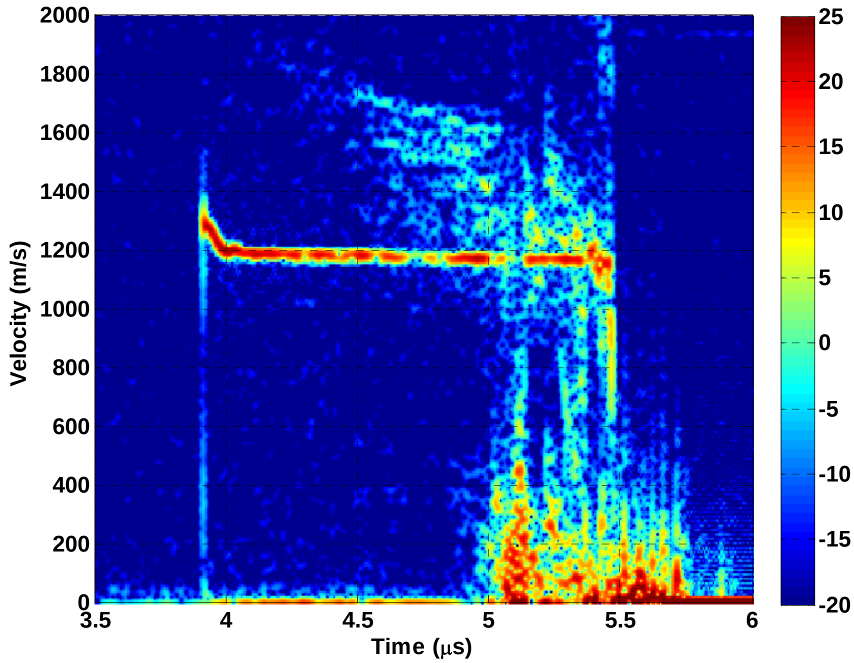

Figure 4: Velocity/time spectrogram produced by a Gabor transform of the data in Figure 3.

The shock generated tin ejecta (shown qualitatively in Figure 4) can be measured quantitatively using a proven technique, referred to as an Asay Foil.[8] An Asay Foil is a thin (usually ~20 mg/cm2 areal density) titanium foil suspended several mm above the shocked surface. When the ejecta particles begin to impact the foil, the foil begins to move as the ejecta transfer their momentum. A velocity probe (like a PDV or VISAR) records the motion of the foil as a function of time. When this motion (and foil mass) information is combined with the shock breakout time at the target surface, one can infer the mass and velocity distribution of the ejecta.

Figure 5 shows an example of Asay Foil data (raw digitizer data) taken with a PDV system in an experiment at Sandia National Laboratory. We fielded simultaneous VISARs and PDVs in a series of probes and experiments that confirmed the agreement with the traditional VISAR method of acquiring Asay Foil data. Note the slow acceleration of the foil near 1.2 µs where the foil is just beginning to move. As ejecta accrete to the foil, it accelerates until the bulk material free surface picks up the foil, near 2.5 µs in Figure 5 (right). It is worth noting that we[9] observed that the PDV seems to be able to acquire useful Asay Foil data in some cases when the VISAR has trouble. This situation occurred at two times in the data shown in Figure 5: (a) near 1.7–2 µs, when the PDV data indicate multiple frequency excitation of the foil (presumably from drumhead oscillations at higher modes); and (b) after 2.5 µs in this data set when the free surface of the shocked coupon has "picked up" the foil to its terminal velocity. Being able to track the Asay foil motion through this time is important to measuring ejecta down to low velocities relative to the free surface. The VISARs (not shown) seem to lose fringe contrast when multiple modes are excited in the foil so in this case PDV may offer some advantages.

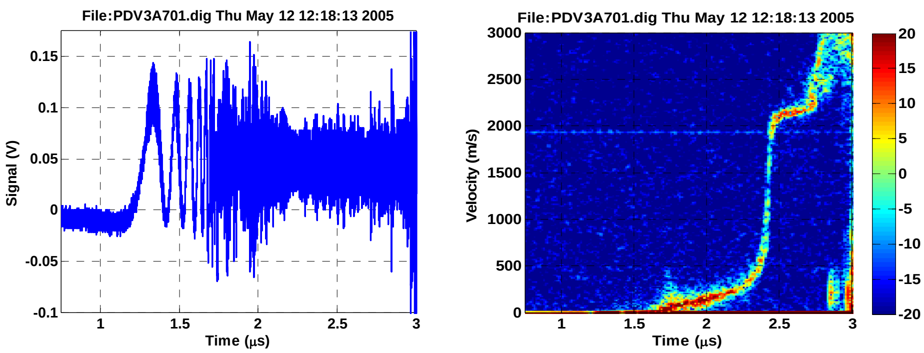

Figure 5: Asay foil data from shocked tin, raw digitizer data (left) and Gabor transformed velocity results (right).

Flyer plate experiments on guns are powered by either gas or energetic powder, and an important element of any experiment is the precise velocity measurement of the impacting plate carried by the sabot. A rather novel application of PDV in such experiments is to use a small optical probe (either a 1 mm diameter collimated lens or a bare fiber probe) mounted through the edge of a target coupon so that it can view the motion of the projectile before it impacts the target assembly.

Figure 6 shows two examples of such data taken with a 1 mm diameter collimated probe. Even though we performed no special preparation of the sabot to improve the signal return, the PDV was able to track the projectile for more than 180 µs before impact (near 0 µs) in left figure. The vertical axis is expanded to show the ~few m/s acceleration of the flyer before impact and illustrates how it is possible to measure the flyer velocity with an absolute accuracy of ± 0.1 to 0.2 m/s. Figure 6 (right) shows a flyer velocity from a two stage light gas gun experiment where upstream trigger pins induced significant oscillations in the sabot/flyer plate and a measurable deceleration is observed during the free flight of the projectile before impact on the target assembly. Such structures in the velocity should be carefully considered when estimating the absolute accuracy of a flyer plate velocity measurement.

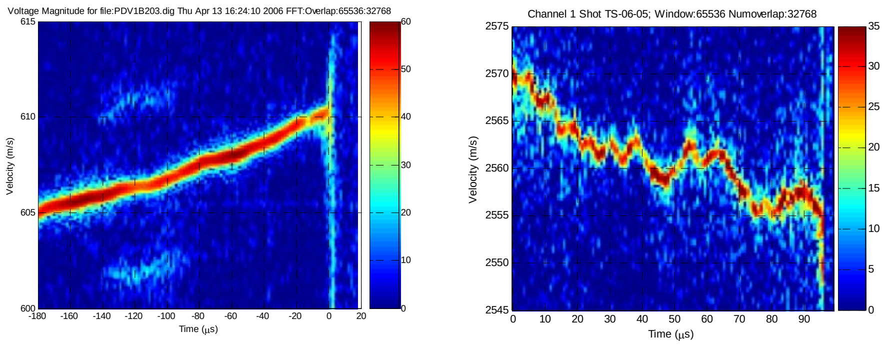

Figure 6: Gabor transform of PDV data of the flyer plate velocity obtained on a single stage powder (left) and two stage light gas gun (right) flyer plate experiment.

In many flyer plate experiments, a transparent window is sometimes used as a shock wave "anvil" to preserve the state of the material under study at elevated pressure. Typical window materials used over the years are lithium fluoride (LiF), quartz, and sapphire, among others. Because the index of refraction of the shocked window is different from the ambient property, one must correct the apparent velocity of the target/window interface for this effect. We recently published results[10] on window corrections for LiF [100], z-cut quartz, and c-cut sapphire at VISAR (532 nm) and PDV wavelengths (1550 nm) for several pressures.

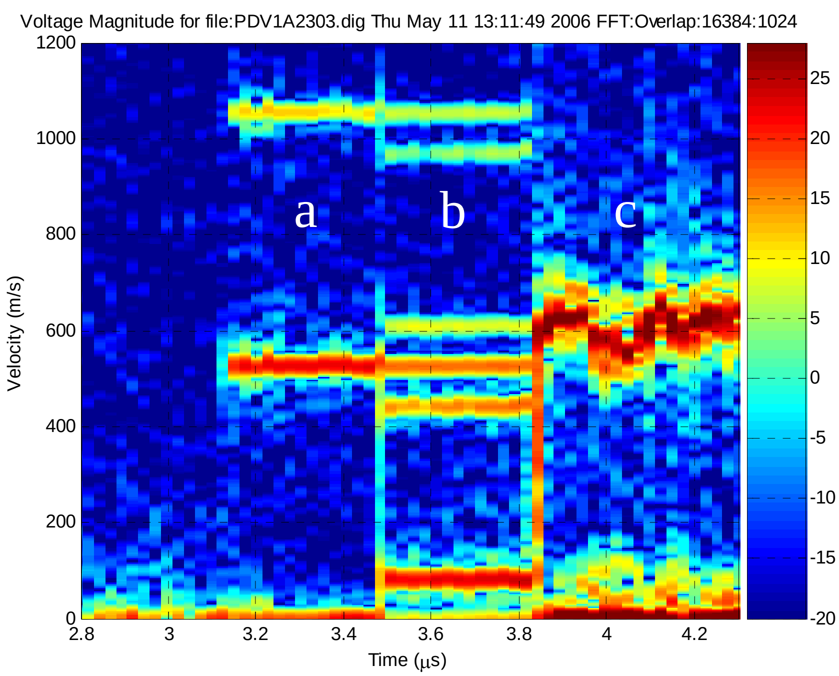

Figure 7: PDV velocity for a symmetric impact experiment (sapphire on sapphire) showing the effect of multiple reflections and frequency mixing. The three time regions (a, b, & c) are described in the text.

Figure 7 shows an interesting example of windowed sample shock velocity data obtained with a PDV instrument. Both the target and flyer plate were sapphire windows (with an aluminum coating at the impact interface for reflectivity). The velocity data is naturally grouped into three time regions: (a) from impact until the shock reaches the downstream free surface of the target window (~3.1 to 3.5 μs); (b) from when the shock reflects in the target window to when it arrives near the impact surface (~3.5 to 3.85 μs); and (c) after the release wave form the back of the flyer intersects the release from the front surface of the window (from 3.85 μs onwards). Region (a) shows the fundamental interface (uncorrected) velocity of about 540 m/s. Because the sapphire window did not have an antireflective coating for 1550 nm light, the Doppler shifted light is reflected from the exit surface of the window and is Doppler shifted a second time producing the weak harmonic velocity near 1080 m/s (visible above the "a" in the figure). In fact, several such Doppler shifts from multiple Fresnel reflections are visible in the data, at lower contrast in the spectrogram (not shown). In region (b), the shock has reflected from the downstream target window free surface as a release. The Doppler shift of the motion of the downstream window surface mixes with the other frequencies present to produce the assortment of lines observed in region (b). When the window spalls (region c), it is launched with tensile wave ringing evident in the velocity trace. For a more detailed discussion of these features, please see reference 10.

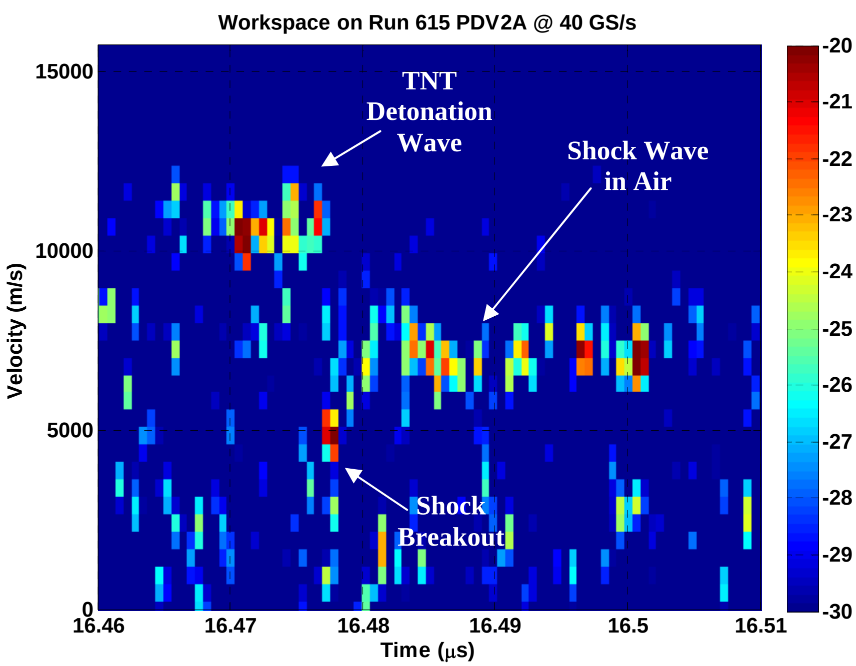

Figure 8: Gabor transform of 40 GS/s PDV data taken on bare TNT. Shock breakout is labeled as is the air shock and apparent TNT detonation wave.

One last example of how PDV may be applied in new ways is shown in Figure 8. In this experiment we used a bare fiber probe to view the free surface of a TNT explosive charge (nominal density of 1.64 g/cm^3). Shock breakout at the free surface of the TNT is visible near 16.477 μs, followed by the PDV measurement of the air shock (~7.4 km/s in Albuquerque - ~5000 ft above sea level).[11] What is interesting is that we appear to be seeing a velocity feature ***before*** the shock reaches the free surface of the explosive. The apparent velocity of this feature is 10.5 ± 0.4 km/s (~13.5 GHz beat frequency).[12] We observed this feature in several identical shots and it appears to be quite reproducible. We interpret this feature as the velocity of the detonation wave (6.95 km/s at this TNT density) modified by the index of refraction of the TNT (estimated to be ~1.5). If this is the detonation wave, then it appears that the PDV is able to "see" 40-50 μm into the material (assuming a 6-7 ns record at 6.95 km/s). Since most high explosives are not entirely opaque at visible and near IR wavelengths, this offers a possibility of measuring properties of explosives inside the bulk material, rather than being limited to surface measurements.

CONCLUSION

PDV is a new implementation of a familiar velocimetry diagnostic and is being developed at several laboratories worldwide. It has the potential to produce data that will give us new insight into several areas of applied and fundamental physics. Because of a favorable combination of low cost, ease of fielding and high performance, we expect that there will be many new applications of this diagnostic in the years to come.

ACKNOWLEDGMENTS

We gratefully acknowledge the helpful advice and collaboration of Ted Strand and his colleagues at Lawrence Livermore National Laboratory. It is a tribute to the quality of Ted's advice that our first PDV instrument worked the very first time we turned it on. We also deeply appreciate the collaboration of our colleagues at Los Alamos National Laboratory who helped us field experiments and built much of the equipment used here (Benjie Stone, Pat Rodriguez, and Lenny Tabaka). We thank our LANL and Sandia colleagues who collaborated on experiments presented here (Dan Dolan, Kevin Fleming, Mike Furnish, Brian Jensen, Russ Olson, Paulo Rigg, and many others) who kindly allowed us to show some of our data here. Our colleagues at NSTec, LLC (formerly Bechtel Nevada) in Los Alamos, Las Vegas, and Santa Barbara have always been a great help in building, fielding, and improving our PDV systems. We particularly acknowledge the help of Doug Devore, Adam Iverson, Bruce Marshall, Vince Romero, and Jason Young of NSTec for their hard work and unfailing help and advice. Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the U.S. Department of Energy's National Nuclear Security Administration and we are grateful for their sponsorship.

REFERENCES

1. Strand, Oliver T., *et al*., "Velocimetry using heterodyne techniques," *26th Int. Conf. on High-speed Photography and Photonics, Alexandria, VA September 19-24, 2004*, Proc. of SPIE **5580** (2005) 593; and Strand, O. T., *et al*., "Compact system for high-speed velocimetry using heterodyne techniques," Rev. Sci. Instr. **77** (2006) 083108.

2. Weng, Jidong, *et al*., "Optical-fiber interferometer for velocity measurements with picosecond resolution," Appl. Phys. Lett. **89** (2006) 111101.

3. Emkey, William L., "A Polarization-Independent Optical Circulator for 1.3 μm," Journal of Lightwave Technology **LT-1**, no. 3 (1983) 466.

4. Yeh, Y., and Cummins, H. Z., "Localized fluid flow measurements with an He-Ne laser spectrometer," Appl. Phys. Lett. **4**, no. 10 (1964) 176; and Foreman, Jr., J. W. *et al*., "Measurement of localized flow velocity in gases with laser Doppler flowmeter," Appl.

Phys. Lett. **7**, no. 4 (1965) 77.
5. We have had good performance from polarization-insensitive circulators and fused fiber couplers from JDS Uniphase (www.jdsu.com) and Agiltron Corp. (www.agiltron.com). All of our fiber lasers are from IPG Photonics (www.ipgphotonics.com) with both 2 and 5 W models (ELR series; higher power models are available). A narrow linewidth (< 100 kHz) offers a long coherence length for flexible experimental fielding. Our favorite detector for many systems is the Miteq model DR-125G (www.miteq.com) which has excellent performance from ~10 kHz to above 13 GHz.
6. Portable cases with rack mounting are available from several vendors; one such vendor is Hardigg Industries (www.hardigg.com).
7. There are several good reference books on short time Fourier transform methods. One comprehensive toolbox (the Time Frequency Toolbox) is in the public domain (tftb.nongnu.org). The Matlab Signal Processing Toolbox also has many useful routines for PDV analysis.
8. Asay, J. R., "Thick-Plate Technique for Measuring Ejecta from Shocked Surfaces," *J. of App. Phys*., **49**, no.12 (1978) pp.6173-6175.
9. Furnish, M. D. and Holtkamp, David B., unpublished (2005).
10. Jensen, B. J., Holtkamp, D. B., Rigg, P. A., and Dolan, D. H., Journal of Appl. Phys. **101** (2007) 013523.
11. Tanguay, V. and Higgins, A. J., Journal of Appl. Phys. **95**, no. 11 (2004) 6159.
12. We used a Tektronix TDS-6154C digitizing oscilloscope for these measurements, which has a sample rate of up to 40 GS/s and a DSP corrected analog bandwidth of ~15 GHz.