Measurement of an explosively driven hemispherical shell using 96 points of optical velocimetry

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Abstract. We report the measurement of the surface motion of a hemispherical copper shell driven by high explosives. This measurement was made using three 32 channel multiplexed photonic Doppler velocimetry (PDV) systems, in combination with a novel compound optical probe. Clearly visible are detailed features of the motion of the shell over time, enhanced by spatial correlation. Significant non-normal motion is apparent, and challenges in measuring such a geometry are discussed.

1. Background and Motivation

The use of laser velocimetry, here called Photonic Doppler Velocimetry (PDV), has become routine in shock measurements [1–4]. Using basic fiber-optic components, it is a relatively easy technique to field. It gives reliable surface velocity measurements while being robust against surface degradation and ejecta. It is also easy to interpret, and can act as a powerful constraint in understanding shock behavior.

In one of the most common applications of velocimetry, a surface is driven with a one-dimensional shock, and a single laser probe is aimed at the surface for characterization. At Los Alamos and other laboratories, we would like to extend the utility of PDV from a tool for characterizing shocks to a tool to understand the behavior of materials in explosively driven experiments. In these experiments, shocks are not one-dimensional, and vary significantly across an interrogated surface. In addition, it is not generally true that the surface motion is normal to the laser probe. For these sorts of experiments, we want to measure as many points as possible to capture the surface motion.

Such a measurement is enabled by two emerging technologies: a high density multiplexing system as well as a compact multi-channel optical probe design. These tools have been developed in extensive collaboration with National Security Technologies (NStec). The optical multiplexing system combines eight PDV signals into one electrical output to be recorded on a 20 GHz oscilloscope. This allows for a very compact MPDV (multiplexed PDV) system recording 32
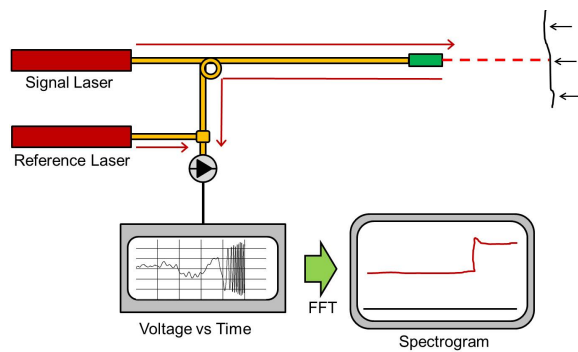
Figure 1. Diagram of a heterodyned PDV arrangement. In this arrangement, two separate lasers are beat together to form the velocimetry signal. The baseline of the signal is the frequency difference between the two lasers.
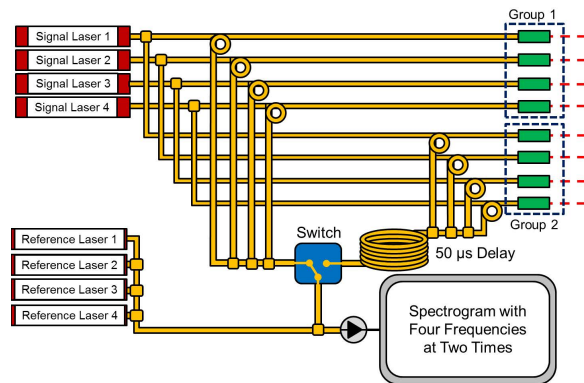
Figure 2. Simplified schematic of the 4 x 2 multiplexing employed in our systems. Combining eight lasers gives four frequency-multiplexed signals, while adding delayed channels and an optical switch allow two time-multiplexed signals.

signals per unit. In addition, a great deal of work has been done to fit this system to a high-density optical probe, which allows for the possibility of hundreds of laser probes in a very small space.

2. Heterodyning and Multiplexing

A typical PDV system detects surface velocities by measuring shifts in reflected laser light. A laser is launched into a fiber and split into signal light and a small amount of reference light. The majority of the light is sent into the signal path and travels through a collimating probe and shines on a surface. Some of the light is scattered back and received by the same fiber, where it can be combined with the reference light from the laser. If the measured surface is moving, there is a shift in the lasers frequency by an amount given by $\Delta f = 2v/\lambda$. Mixed with the reference light, this shift manifests as a beat frequency on a photodetector at a frequency equal to Δv.

There is no requirement that the light be mixed with the transmitting laser. In a heterodyning scheme, reference light is not split from the signal light. Instead, a second laser acts as the reference for the recollected light. The result is that rather than having a measured beat frequency that starts at zero and increases, one can have an arbitrary baseline frequency and increase from there. This has two advantages over the traditional scheme: First, it shifts the signal away from zero frequency, where there is usually a great deal of electrical noise. Secondly, it allows for combining a number of signal/reference pairs at different offset frequencies.

Figure 1 shows a simple picture of the multiplexing employed here. Four signal/reference laser pairs combine to give four velocimetry signals with varying frequency shift. In addition, we employ an optical switch and time delay to record another four signals, delayed in time by 50 μs. In this way, eight separate PDV probes are combined and recorded on one scope channel. Splitting each laser four ways and multiplying the fiber components four times allows each MPDV unit to output 32 total velocimetry channels across four oscilloscope inputs.

Combining this many PDV channels into one scope trace enables very compact recording and large channel counts for surface measurements. It does not come without cost, however. First, there are a number of artifacts imposed on the recording system, such as stray baselines, crosstalk and mixing products which can complicate the signal. This makes automated signal
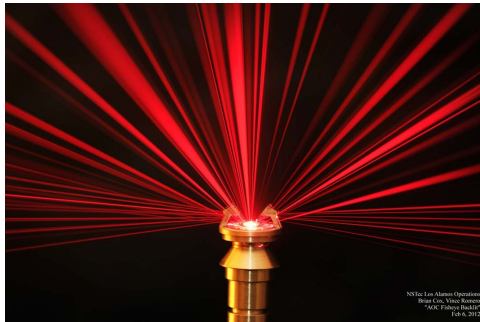
Figure 3. Image of the 120 channel optical probe used in the experiment. Photo by Brian Cox and Vince Romero, NStec, 2012.
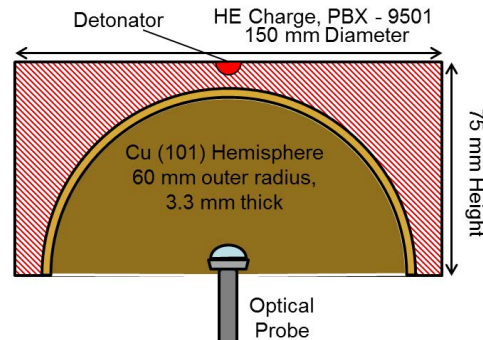
Figure 4. Cross section of the experiment. A 75 mm diameter cylindrical charge of PBX 9501 surrounds a 3.3 mm thick copper hemisphere. The top corresponds to polar angle zero degrees, and increases to 90 degrees in the horizontal plane.

extraction difficult, and adds complication to the analysis. Second, frequency multiplexing reduces the number of effective bits-per-channel during digitization. The practical result of this is a reduction in the dynamic range of the system so that weak signals can be lost.

In parallel with the ability to record many PDV channels at once, it is important to mention advances in extraction capability. NStec has also put great effort into developing software tools that allow for rapid, bulk extraction of many traces at once. Without such tools, extraction of 100 channels or more becomes extremely time consuming.

3. Advanced Optical Cavity Probe
The second enabling technology for this experiment was the development of the Advanced Optical Cavity Probe. In a typical velocimetry experiment each PDV beam is sent and received through a separate collimating lens. For dense coverage of a surface, fielding 100 or more discrete probes becomes unwieldy if not impossible. This is exacerbated by the tight space requirements common in explosive experiments. To address this problem, a great deal of work has been done to design and refine optical probes that accomplish three things: Take up as little space as possible, direct laser beams across a large range of angles, and collect enough return light from the surface to give a usable velocimetry trace.

The construction of the probe for this experiment featured two main parts: an array of fibers at the base of the probe, as well as a series of lenses which spread the beams while maintaining a suitable focus. A thin disk ~5 mm in radius has an array of small holes drilled in it, into which just over a hundred fibers are inserted. The fibers are all cut and polished together a single bundle. The fiber array is set into the base of the optical lens assembly, which resembles a fisheye lens. Depending on the location of each individual fiber at the base of the lens assembly, the light from it was directed in different directions. After the probe is assembled, we spent several days mapping out the direction of each beam in space. This way, rather than attempting to point each beam in a precise direction, measured the direction of each beam and downselected the probes to be used. A more complete description of this probe can be found in [5].

4. Geometry of the Experiment
As a demonstration of the MPDV system and advanced optical probe, we performed a dynamic experiment using a copper hemisphere driven by high explosive. As seen in the figure 4, the copper was 60 mm in outer radius and 3.3 mm thick. A cylindrical charge of PBX 9501
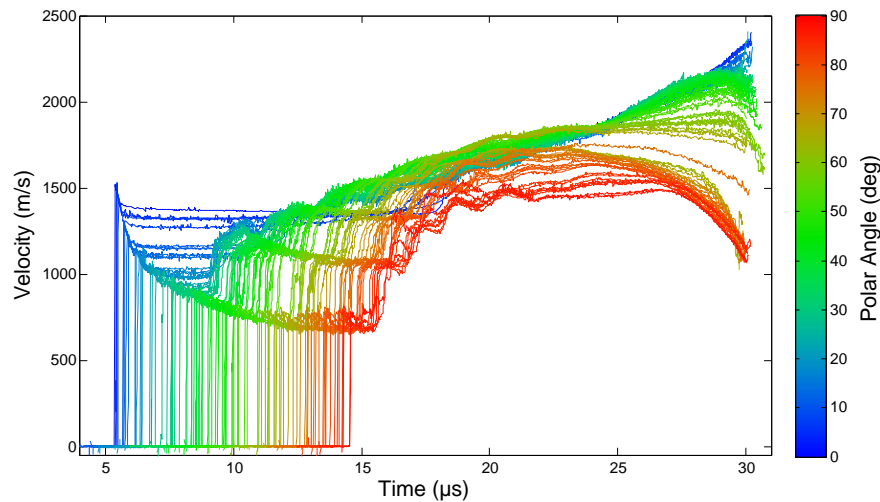
Figure 5. Overlay of all the velocity traces taken during the experiment. Regions of the hemisphere closest to the detonator (polar angle 0) break out earliest.

surrounded it, and the detonator was placed at the top of the charge along its cylindrical axis. Since the package is cylindrically symmetric, it is reasonable to collapse the description to a two dimensional geometry in which polar angle zero is aligned with the axis, pointing up towards the detonator. The optical probe was raised above the hemispheric center of the copper by about 10 mm, as a test to the ability of the probe to shine lasers below polar angle $90°$.

Copper is a good reflector and we expected plenty of return light. If the surface was too smooth, however, most of that light would not get recollected. To prepare the surface, the copper was roughened using a scouring pad. This removed machine marks that could form a diffraction fan, and also kept the surface from being too mirror-like.

It is important to recall a fundamental fact of laser velocimetry measurements: That the surface velocity measured is only that component aligned with the beam itself. In this geometry the probe beams were not aligned with the direction of the surface motion, so the velocity records are systematically low. In addition, the surface was sliding across the beams as it moved, so that the geometry of the surface motion must be accounted for as well. Given these issues, we do not attempt to reconstruct the complete motion. Rather, we can account for these effects in modeling, and use the data to bound the model.

5. Data return

Overall, the data returned from the experiment was very good. Figure 5 shows all the data traces superimposed. Some features in the data are apparent. The detonation wave driving the copper shock arrived earliest at the pole, where the jumpoff velocity was very high. This was partly due to the surface normal angle of the probe beam, and largely due to the normal direction of the shock. For larger polar angles, the jumpoff velocities were reduced by the sweeping nature of the shock moving around the outside of the hemisphere. For all traces, and especially visible for higher polar angles, there was an oscillation which is consistent with ringing within the copper shell.

For late times, the surface accelerated at low polar angles and appeared to decelerate for higher polar angles. For low polar angles, near the center of the assembly, this is close to the true motion as the surface was approaching the probe more or less directly. For directions near the horizon, however, the surface was sliding rapidly across the probe beams. The apparent
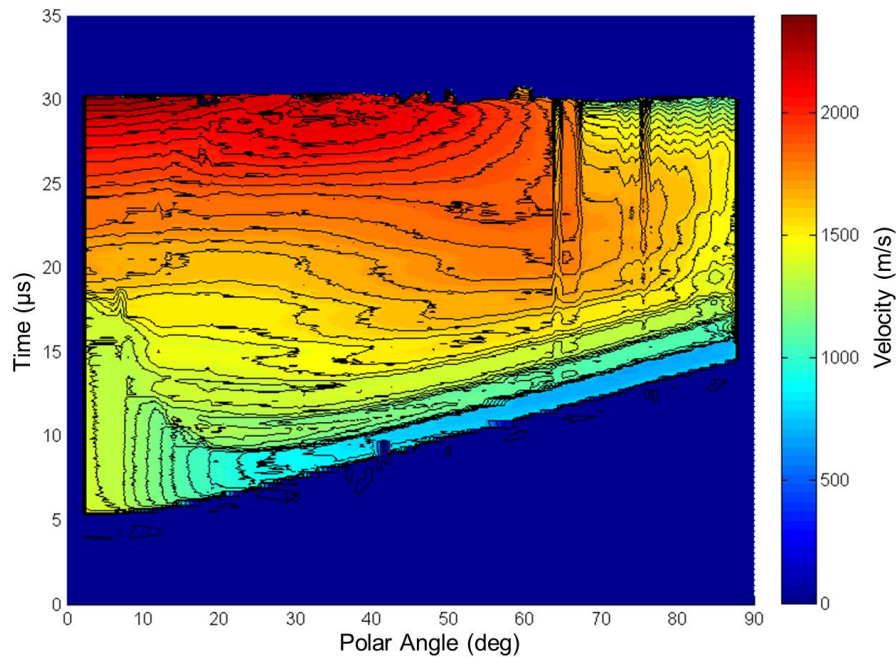
Figure 6. Contour surface showing velocity traces returned from the experiment. The horizontal axis is polar angle of the probe, the vertical axis is time, and the height of the surface is velocity in m/s. Contour lines are separated by 50 m/s.

deceleration is really an artifact of the dynamic geometry of the experiment, as the hemisphere turns inside out the surface was beginning to move perpendicular to the beams.

One of the strengths of high-density velocimetry coverage is the ability to compare neighboring probes to find spatially correlated features. Figure 6 shows a contour plot constructed by interpolating between the 96 probes. Polar angle runs across the bottom, time runs in the vertical direction and the height is given by measured velocity. For early time, there is good agreement between the motion of neighboring probes, showing the structure of the shock breakout as it moved around the shell. In contrast, neighboring probes differ for late times in the region between 60 and 80 degrees. This is not a physical discontinuity, but results from the fact that different probe beams originated from different places on the probe. For very late times, they are seeing different regions of the metal interior, and diverge in the measurement. Because we viewed the surface from different angles, this actually adds additional constraints to the motion.

6. Conclusion

We have successfully measured 96 discrete points of velocimetry across the interior surface of a dynamically driven copper hemisphere. This measurement demonstrates the technique of high density velocimetry coverage, and is enabled by two rapidly emerging technologies: compact and high-density optical probes as well as high-channel count multiplexing of velocimetry channels. The experiment of the and gives a fairly complete view of the motion. While the measured velocities are modified by the geometry of the experiment, a complete picture of the dynamics can be obtained in collaboration with modeling efforts at Los Alamos.

References

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