Extracting Short Rise-Time Velocity Profiles With Digital Down-Shift Analysis of Optically Up-Converted PDV Data

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Presented to 5th Annual PDV Workshop, Ohio State University

September 8-9, 2010

Related NSTec Site-Directed Research & Development Projects:

- •2008: Many-point Velocimetry using Heterodyne Techniques
- •2006: Dynamic Shock Source
- •2006: Time Frequency Analysis

This work was done by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy.

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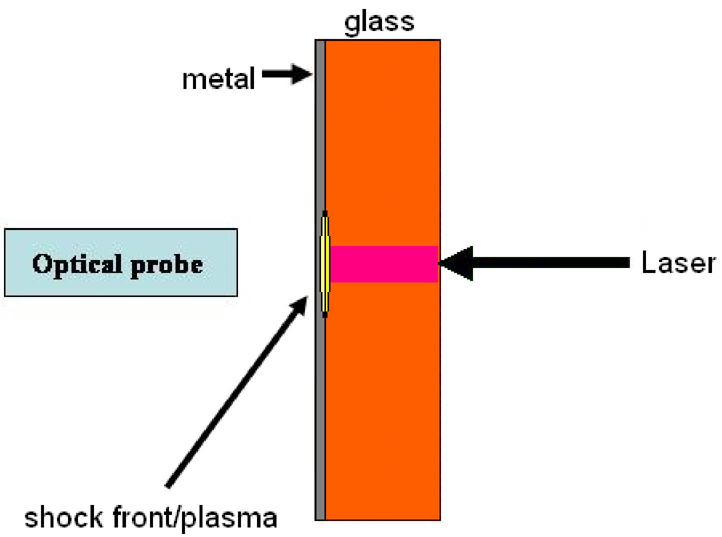
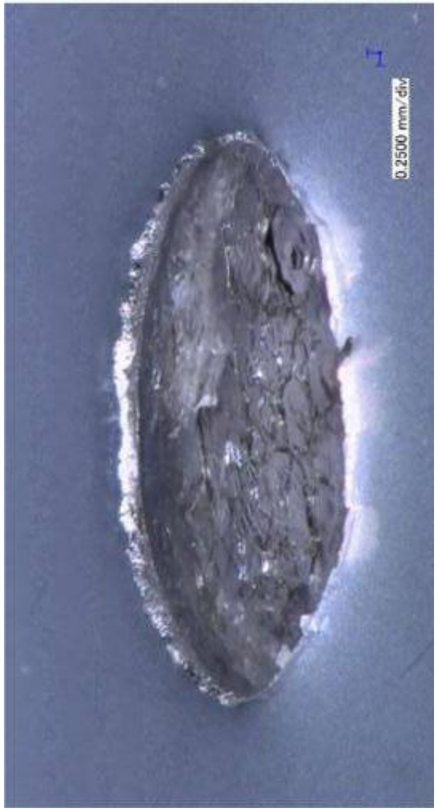
Topics

- Principle of Laser Shock Source
- Optical Up-Converted PDV
- Description of Digital Down-Shift (DDS) Analysis
- Analysis Procedure for Laser-Driven Shock Data
- DDS Analysis Results (plus Other Analysis Techniques)
- Future Work
- Conclusion
- Appendix

Principle of Laser Shock Source



Generation of the shock

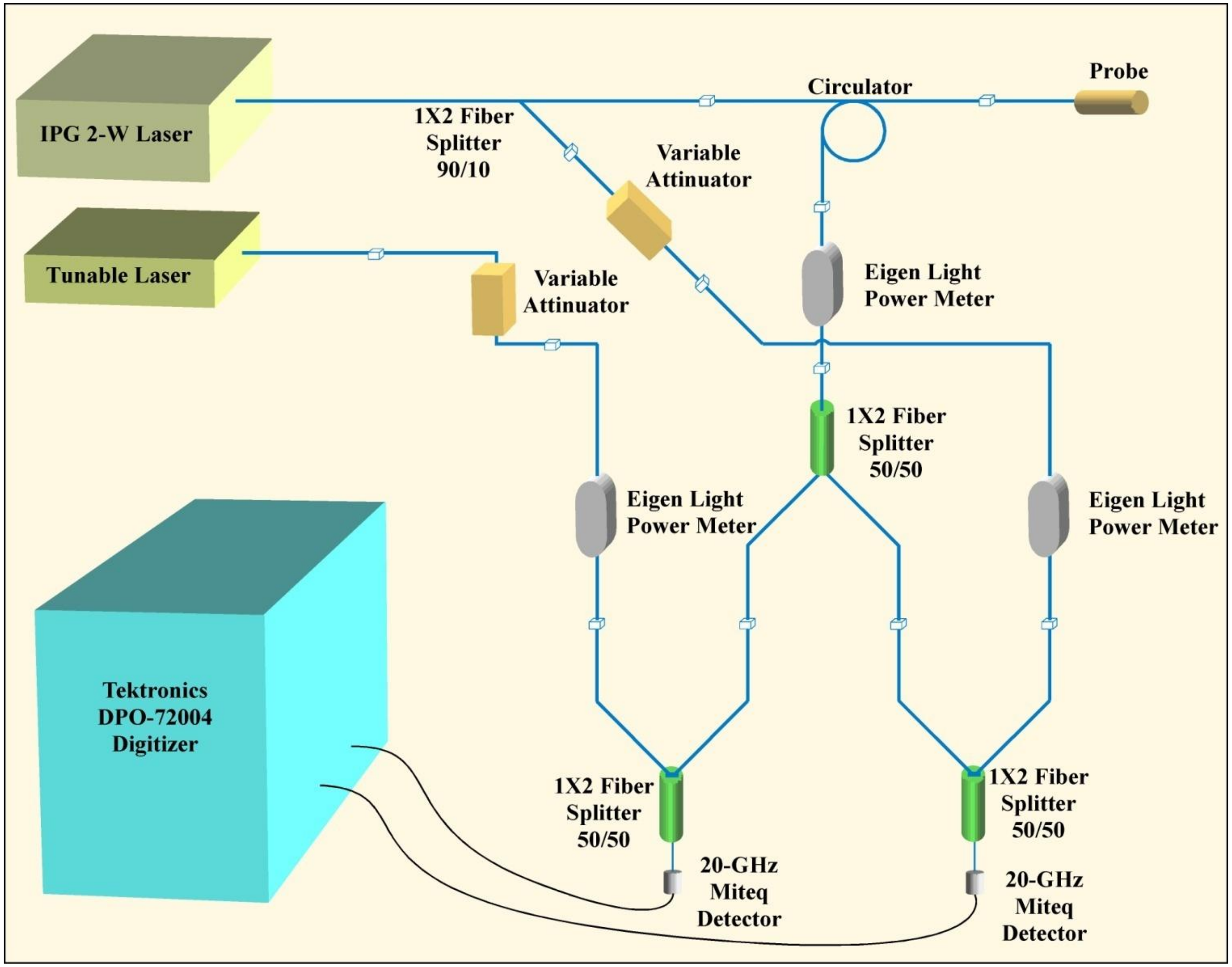


1 mm diameter

Optical Up-Conversion: Setup

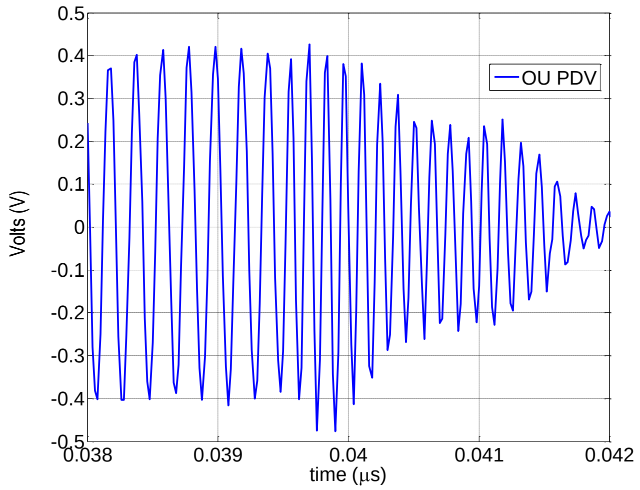
Acquisition of optical up-converted PDV. The up-converted channel is generated by mixing the reflected light with light from a laser that is tuned to produce an apparent positive velocity.

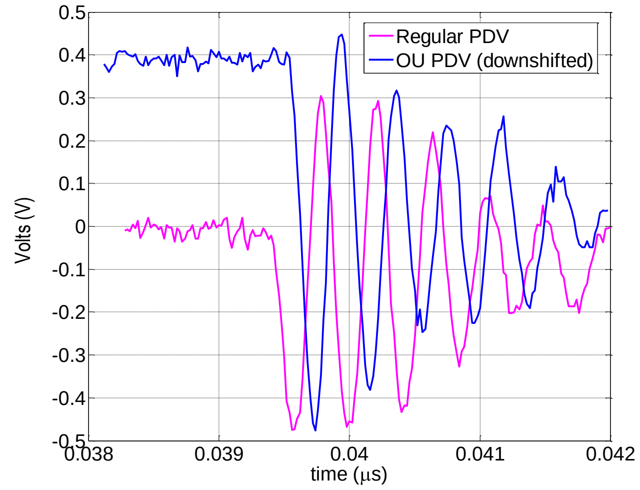
The optical up-shifted signal does not suffer from baseline noise as with the standard PDV.



Optical Up-Conversion: Laser-Driven Shock

- David Holtkamp Challenge:
  Can we get timing information from the DDS of optically up converted PDV data?
- Upper plot shows optically up-shifted PDV data at 3834.28 m/s ~ 5 GHz
- Lower plot shows standard PDV data and digital downshift of optically up-shifted data. Acquired on same shot—note similarity
- Looks like standard PDV data
- Digital downshift at up-shift baseline recovers zero velocity at normal shock breakout; enables breakout in optically up-converted data to be observed easily. We will show that we can extract velocities prior to normal shock breakout at DDS velocities just above base line.



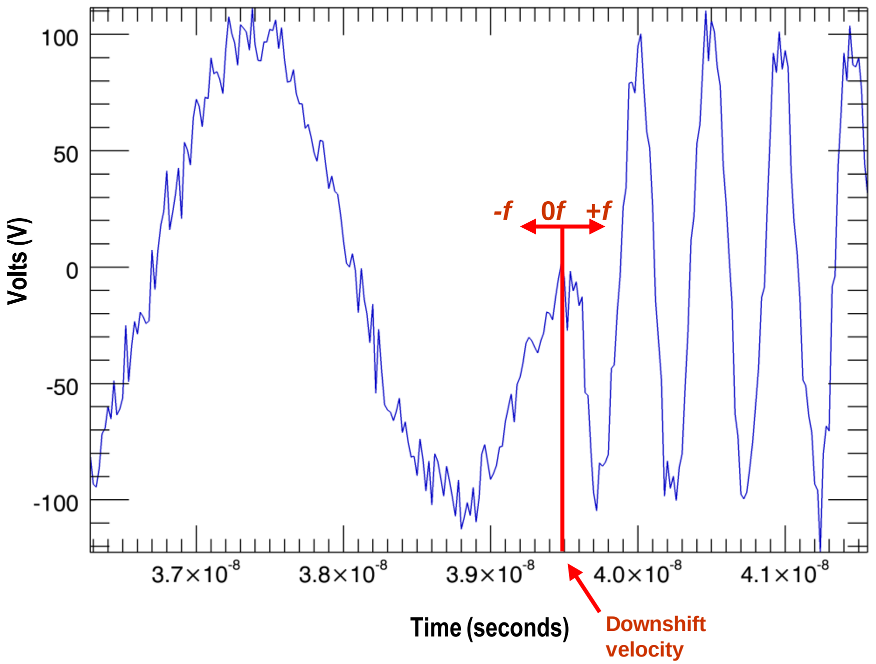


Digital Down-Shift Analysis

- Digital down-shift analysis is a novel technique for the analysis of optically up-converted PDV data
- For each selected frequency (velocity), a constant frequency is subtracted from all signals in the PDV data
- When (time) the down-shift velocity equals the combined true velocity and up-converted baseline, an apparent velocity reversal appears
- We call these reversals "Anomalous" when they occur in the mid-range of the data (near 0) rather than at the peak and trough locations. We seek them because they are easier to identify because they are anomalous.
- The result is that dependent and independent variables are reversed from usual practice v(t), rather velocities are selected and corresponding times are extracted, t(v)

Anomalous Reversal

- In order to determine the time at which the specific velocity corresponding to the downshift is observed, an apparent reversal of the reflector velocity is sought
- This reversal occurs when the combined true velocity and up-shifted baseline equals the digitally down-shifted velocity
- The velocity reversals may be extracted from the data by finding the corresponding reversal in phase in the breakout region
- Example shown is shot 11A (simulated) at up-shift of 4112.26 m/s corresponding to ~285 m/s
  - phase reversal is visible at 0.3954 μs

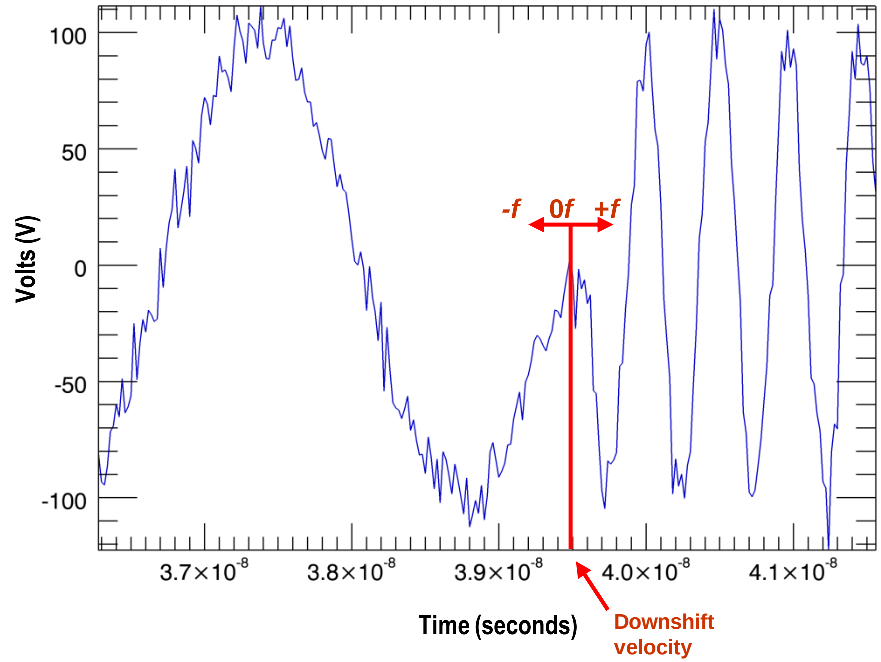


Selecting Down-Shift Velocities

- It is desirable to select a down-shift velocity which produces a reversal which is easily distinguished from an ordinary peak or trough in the signal

- (Condition data – peak/trough) This is accomplished by selecting a down-shift velocity which produces an integer number of cycles ¼ from the beginning of the data, as shown (*X* is a nonnegative integer ¼)

- By incrementing *X*, an array of down-shift velocities is defined whose corresponding time values are subsequently determined



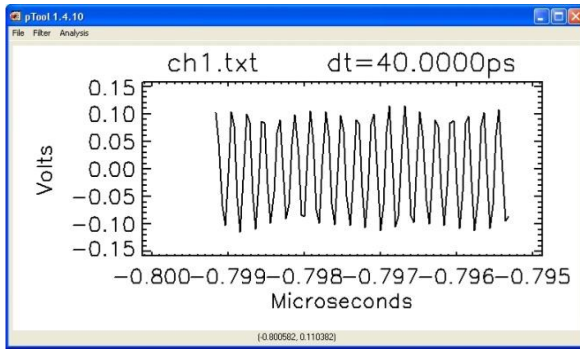
$$V_{DDS}(X) = \frac{X}{(t_b - t_0)}\left(\frac{\lambda}{2}\right) + V_0$$

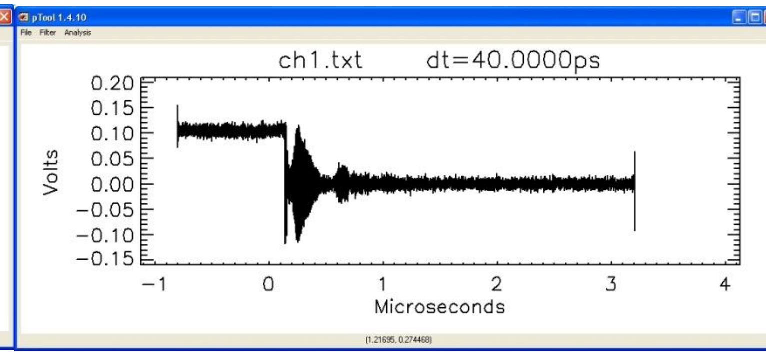
Conditioning the data

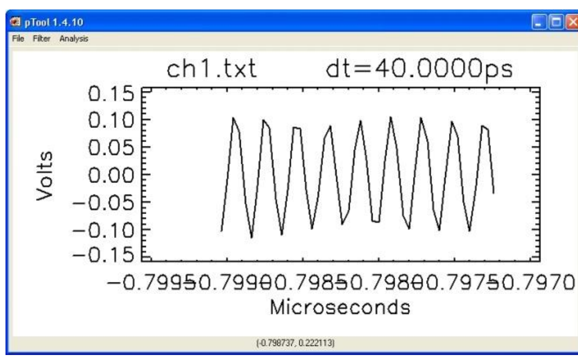
- Edit the data to start at a peak produces a positive baseline at the amplitude of the oscillations before breakout.

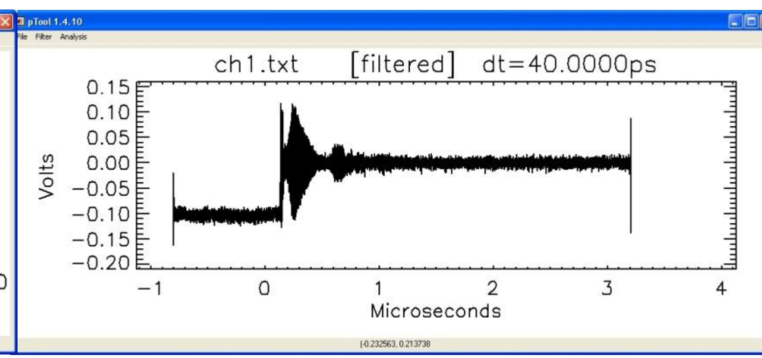
- Edit the data to start at a trough produces a negative baseline at the amplitude of the oscillations before breakout.

- In general, the phase at which the data set begins determines the value and sign of the DDS.









Localizing the Velocity Reversal

- For each selected down-shift velocity, the velocity reversal must be isolated to determine the corresponding time

- A region of interest is defined in which the reversal appears as the extremum of a unimodal function, which can then be more precisely located with a curve fit

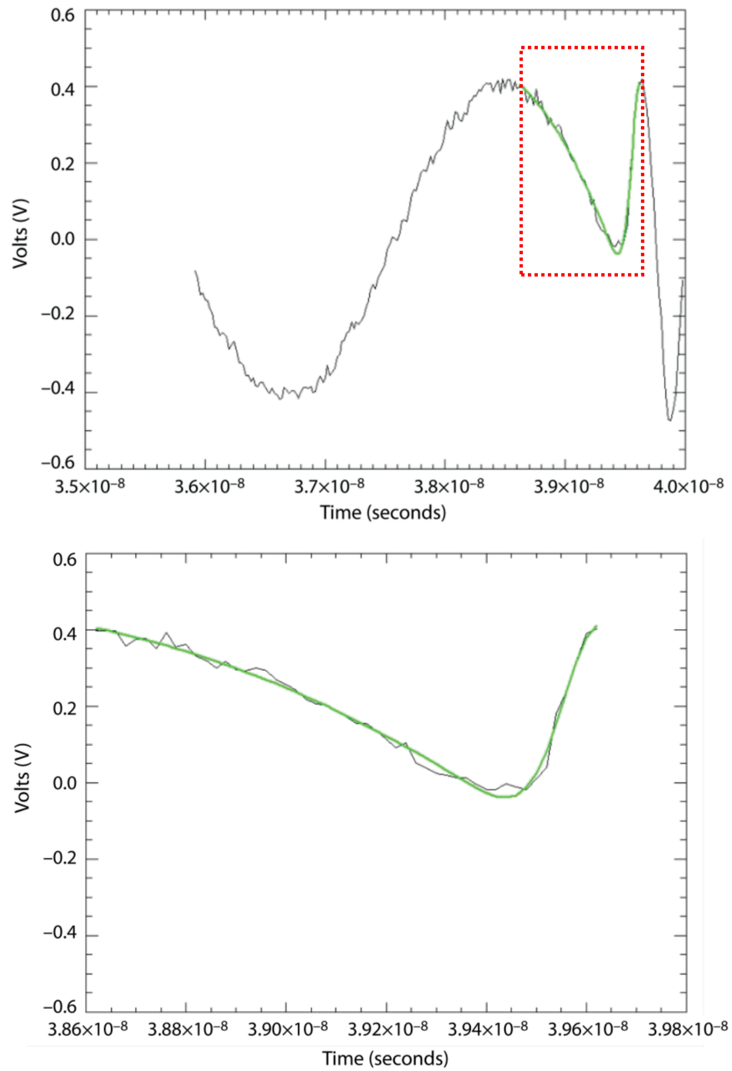
- A peak fit is used for this purpose. One that will accommodate a variety of peak shapes with minimal *a priori* assumptions is preferred

Localizing the Velocity Reversal

- An example is shown here—down-shift velocity corresponds to 4050 m/s with a 3800 m/s up-shift baseline
- The region of interest is defined by selecting ¼ cycle of data on each side of the estimated shock breakout according to

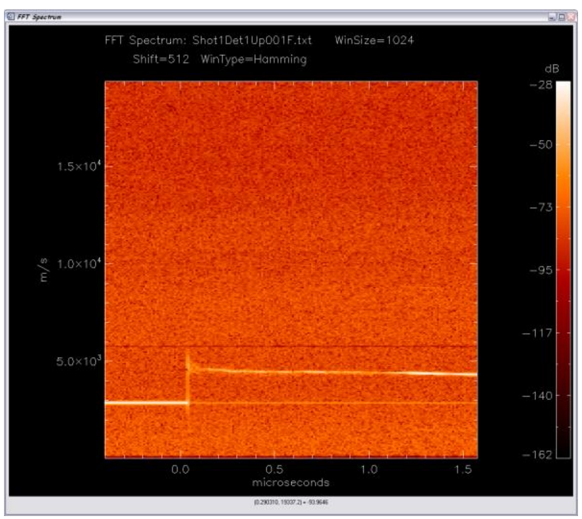
$$t_{+,-} = t_b \pm \frac{1}{8 f_0}\left(\frac{c}{V_{base} - V_{DDS}(X) + V_{+,-}}\right)$$

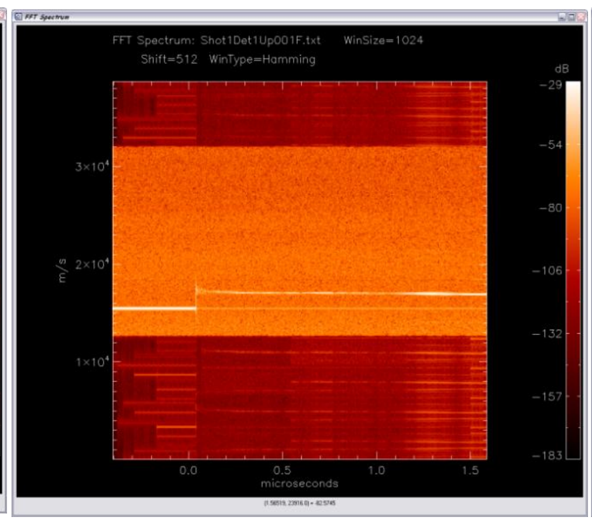
- A peak fit is applied over this interval, which is then minimized to locate the reversal (also applys to throughs)

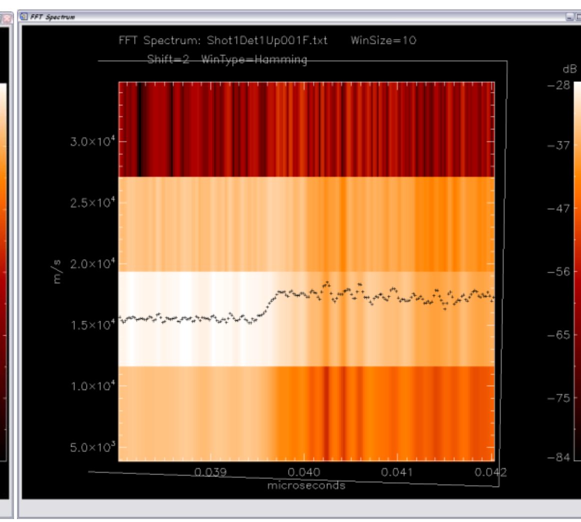


Analysis Process – FFT/ADC

1. Filter (remove clock noise, harmonics, low frequencies)
2. Resample up by 2 / digital up-shift by 12,610m/s (to 20 GHz)
3. FFT (100ps window and 20 ps shift) -- Matthew Briggs: Most everyone uses 1024 pt FFTs. What are actually the best choices?
4. ADC – Omega Filter

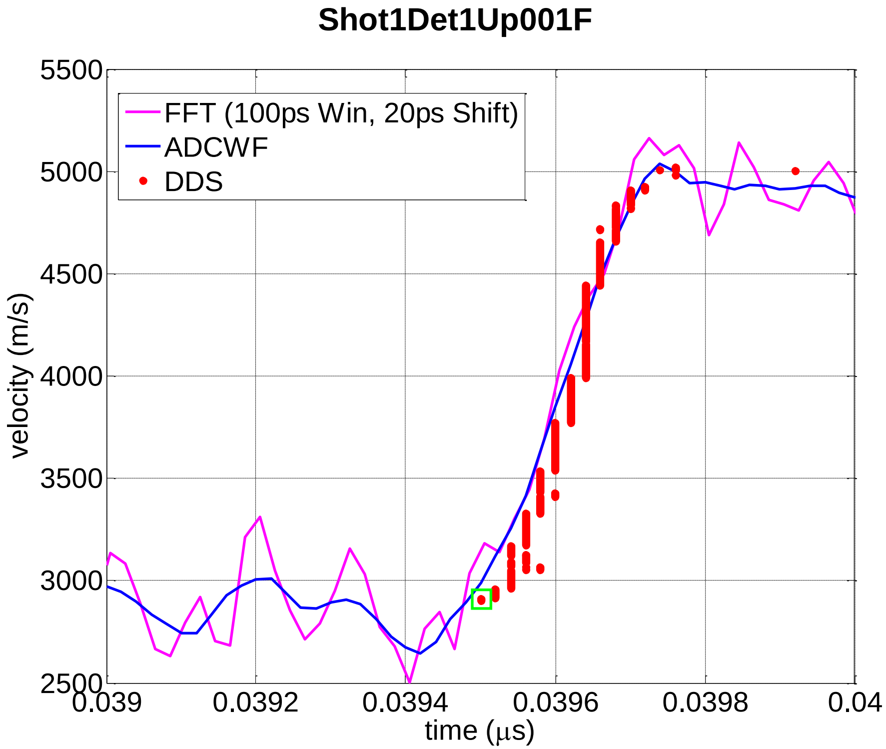


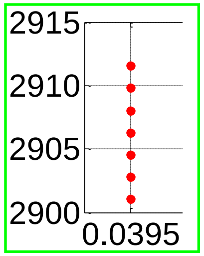




Results From Laser-Driven Shock Data

- Time scale shown is ~1 ns
- The DDS analysis was able to extract a rise time of ~200 ps
- The lowest velocity resolved by the DDS analysis is ~1 m/s—well before normal shock breakout; velocities are extracted over 3 orders of magnitude
- Time resolution is limited by digitizer—20 ps in this case
- Analysis extracts a range of velocities for each time value
- FFT uncertainties consistent with Dan Dolan’s estimate

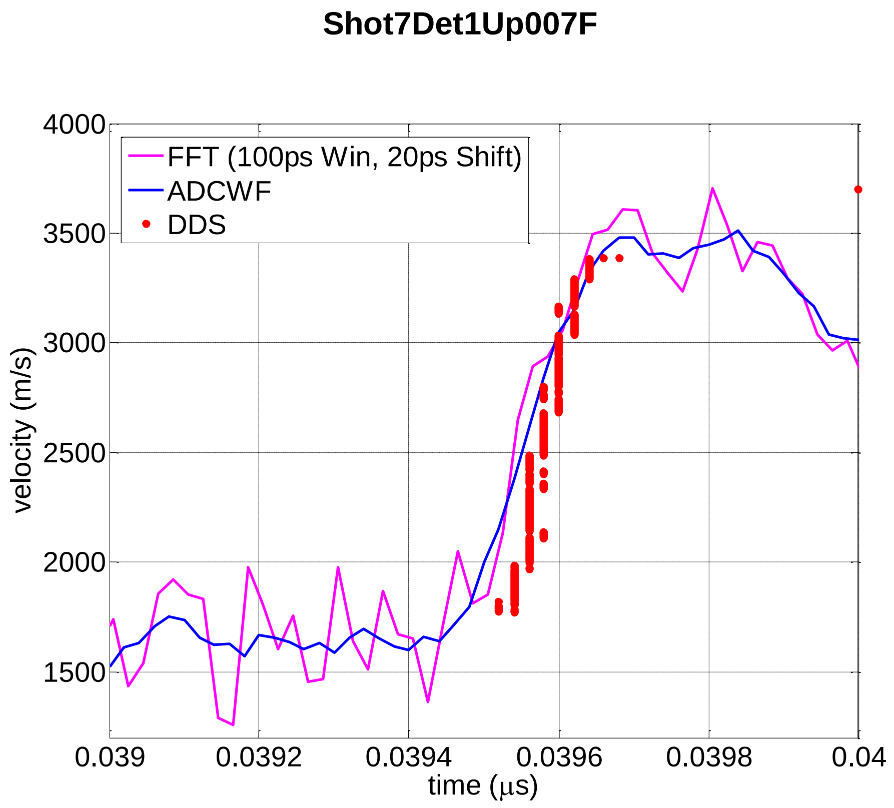




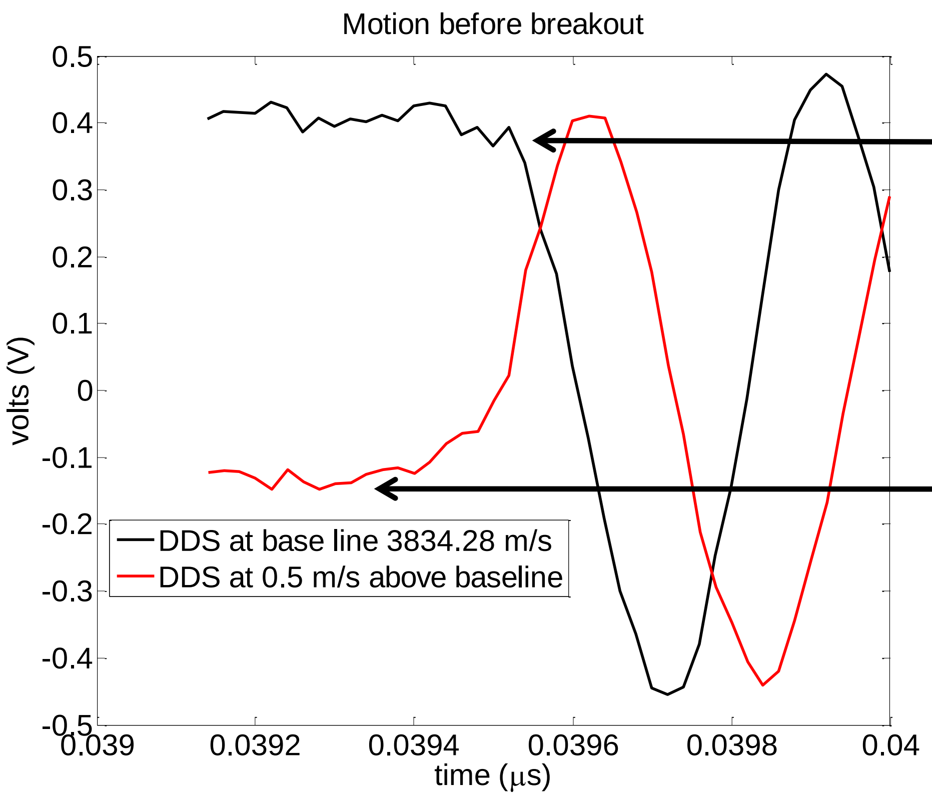
Velocity variation
Within time window

Results From Laser-Driven Shock Data

- Time scale shown is ~1 ns
- DDS analysis extracts less than 200 ps rise time—FFT and ADC are similar
- The lowest velocity extracted is ~40 cm/s
- Analysis of additional datasets from same source can be found in the appendix; results shown are typical



DDS Can Recover Motion Prior to First Fringe Peak, Prior to Normal Breakout



DDS at base line looks like regular PDV. Breakout at 0.0394-0.0395 μs

DDS at ½ m/s above base line. This motion occurs at 0.0393 μs some 100-200 ps before breakout.

Future work

- Very good fit for the multiplexed data
- Use DDS to extract peak velocity from data
- Track migration in zero-crossings using digital down-shift and digital up-shift to determine average velocities between the zero-crossings
- Combine DDS analysis with FFT analysis for input to ADC filtering

Conclusions

- We have presented an entirely new technique for sub-nanosecond velocimetry from single-channel data.
- An apparent velocity reversal appears when the down-shift velocity equals the combined true velocity and up-converted baseline.
- The reversals occur at times corresponding to down-shift velocities.
- The DDS velocity profile is constructed by repeating down-shift velocities and extracting corresponding times. This is in contrast to traditional methods.

Conclusions (cntd)

- DDS can recover motion prior to “breakout”.
- DDS is a very good fit for analyzing the multiplexed PDV data
- 20 ps or better time resolution allows examination of very short rise times of ~200 ps
- Resampling and up-shift permits use of the very short FFTs.

Appendix: Adaptive Down Conversion (ADC)

1. Start with a first order estimate for velocity, $v^{(1)}(t)$, such as that which might be obtained from FFT analysis.
2. Convert first order velocity to frequency, $f^{(1)}(t) = \dfrac{v^{(1)}(t)}{(\lambda/2)}$.
3. Integrate frequency to generate phase, $\phi^{(1)}(t) = 2\pi \int_{-\infty}^{t} f^{(1)}(t')dt'$.
4. Generate mixing functions, $\cos(\phi^{(1)}(t))$ and $\sin(\phi^{(1)}(t))$.
5. Multiply the data, D(t), by the mixing functions:

$$PC(t) = \cos(\phi^{(1)}(t)) \times D(t) = \frac{A(t)}{2}\{\cos(\phi(t) - \phi^{(1)}(t)) + \cos(\phi(t) + \phi^{(1)}(t))\},$$

$$PS(t) = \sin(\phi^{(1)}(t)) \times D(t) = \frac{A(t)}{2}\{\sin(\phi(t) - \phi^{(1)}(t)) + \sin(\phi(t) + \phi^{(1)}(t))\}.$$

Appendix: ADC (cont'd)

6. Low-pass-filter these products to produce residual functions:

$$LC(\phi(t)-\tilde{\phi}(t)) = \frac{A(t)}{2}\cos(\phi(t)-\tilde{\phi}(t))$$

$$LS(\phi(t)-\tilde{\phi}(t)) = \frac{A(t)}{2}\sin(\phi(t)-\tilde{\phi}(t))$$

7. Generate I as

$$I(t) = 2\times\left[LC(\phi(t)-\tilde{\phi}(t))\times\cos(\tilde{\phi}(t)) - LS(\phi(t)-\tilde{\phi}(t))\times\sin(\tilde{\phi}(t))\right].$$

8. Generate Q as

$$Q(t) = 2\times\left[LS(\phi(t)-\tilde{\phi}(t))\times\cos(\tilde{\phi}(t)) + LC(\phi(t)-\tilde{\phi}(t))\times\sin(\tilde{\phi}(t))\right].$$

9. Unfold continuous phase (i.e., accounting for 2π jumps in phase)

$$\phi(t) = \tan^{-1}\left(\frac{-Q(t)}{I(t)}\right).$$

Appendix: ω Filter

Computing time derivative with Fourier Transform: ω Filter

In-phase signal: $I(t) = A(t)\cos(\phi(t))$

Out-of-phase signal: $Q(t) = -A(t)\sin(\phi(t))$

$$\frac{d}{dt} I(t) = FFT^{-1}\left[\left(\frac{2\pi k}{N} i\right) FFT \blacksquare(t)\right]$$

$$v(t) = \left(\frac{\lambda}{4\pi}\right) \frac{Q(t)\frac{d}{dt}I(t) - I(t)\frac{d}{dt}Q(t)}{\sqrt{I^2(t) + Q^2(t)}}$$

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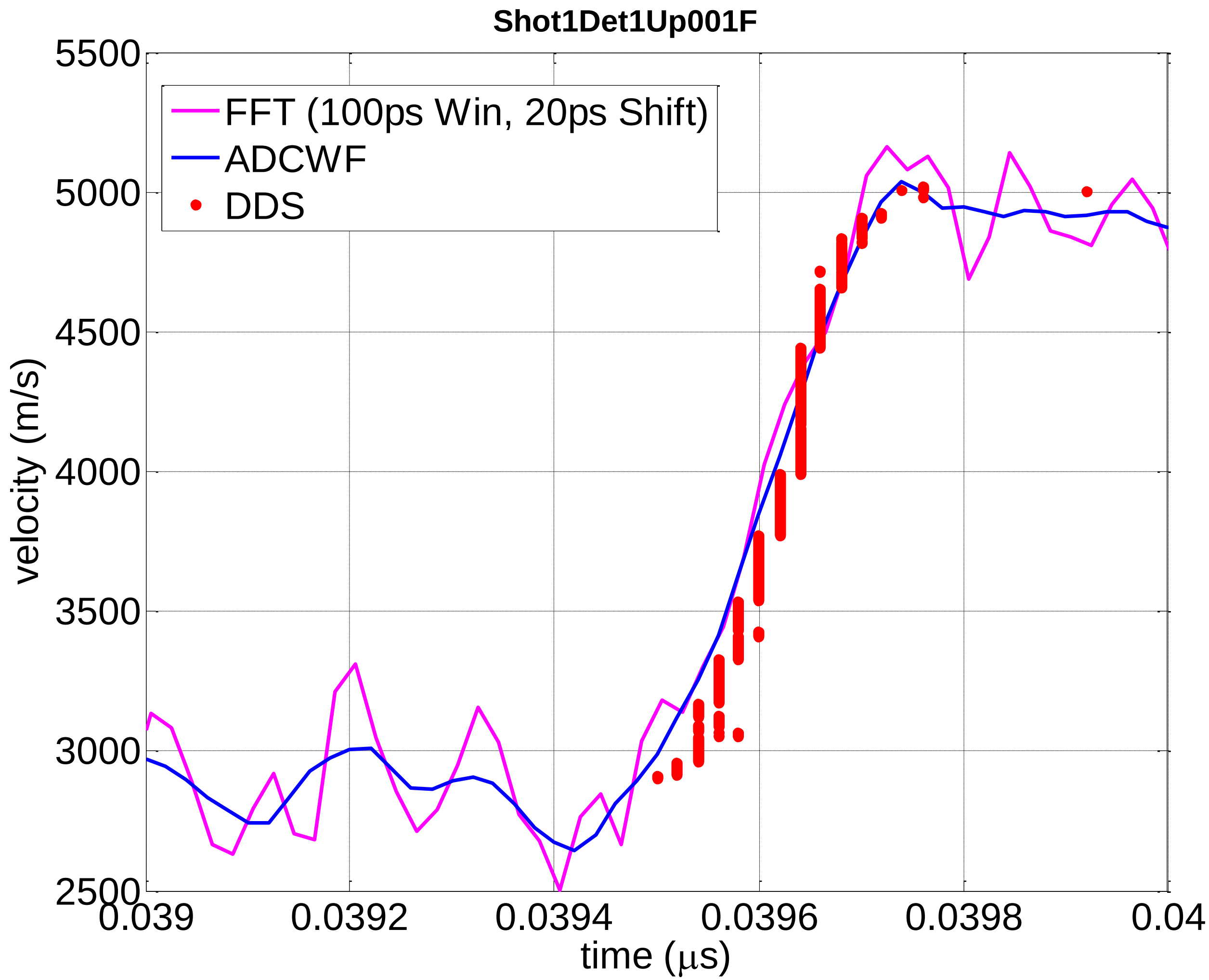
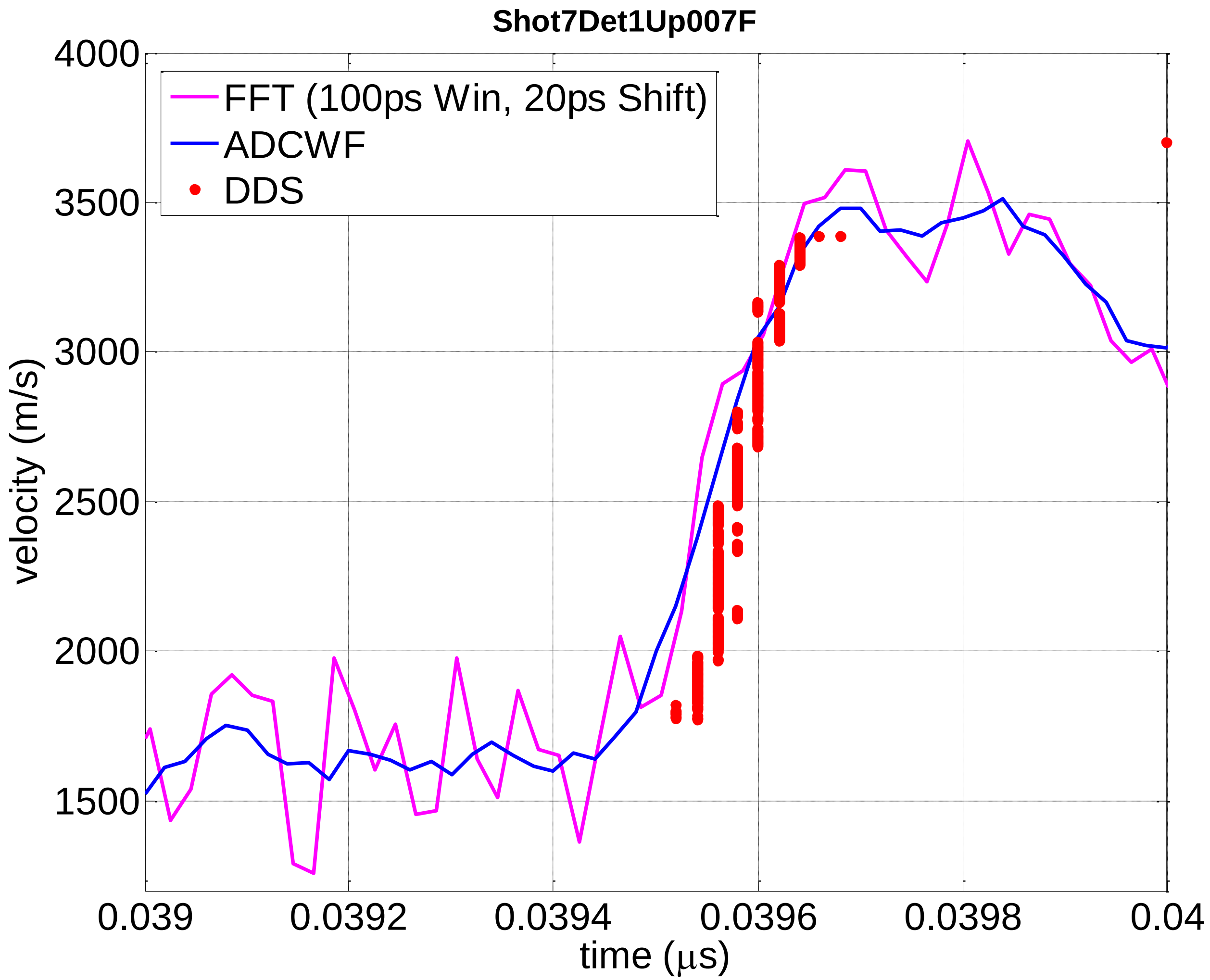
Appendix: Results



Appendix: Results



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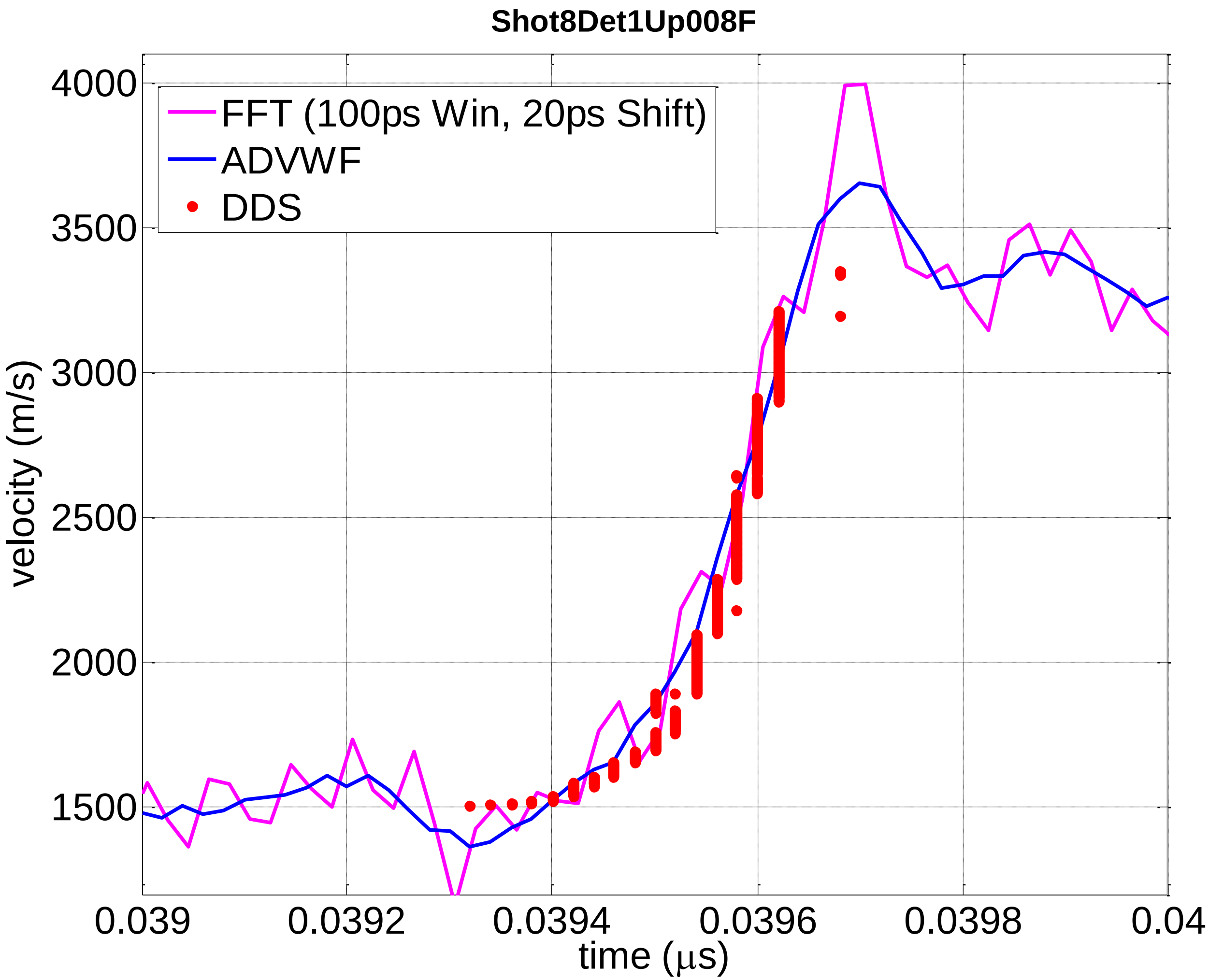

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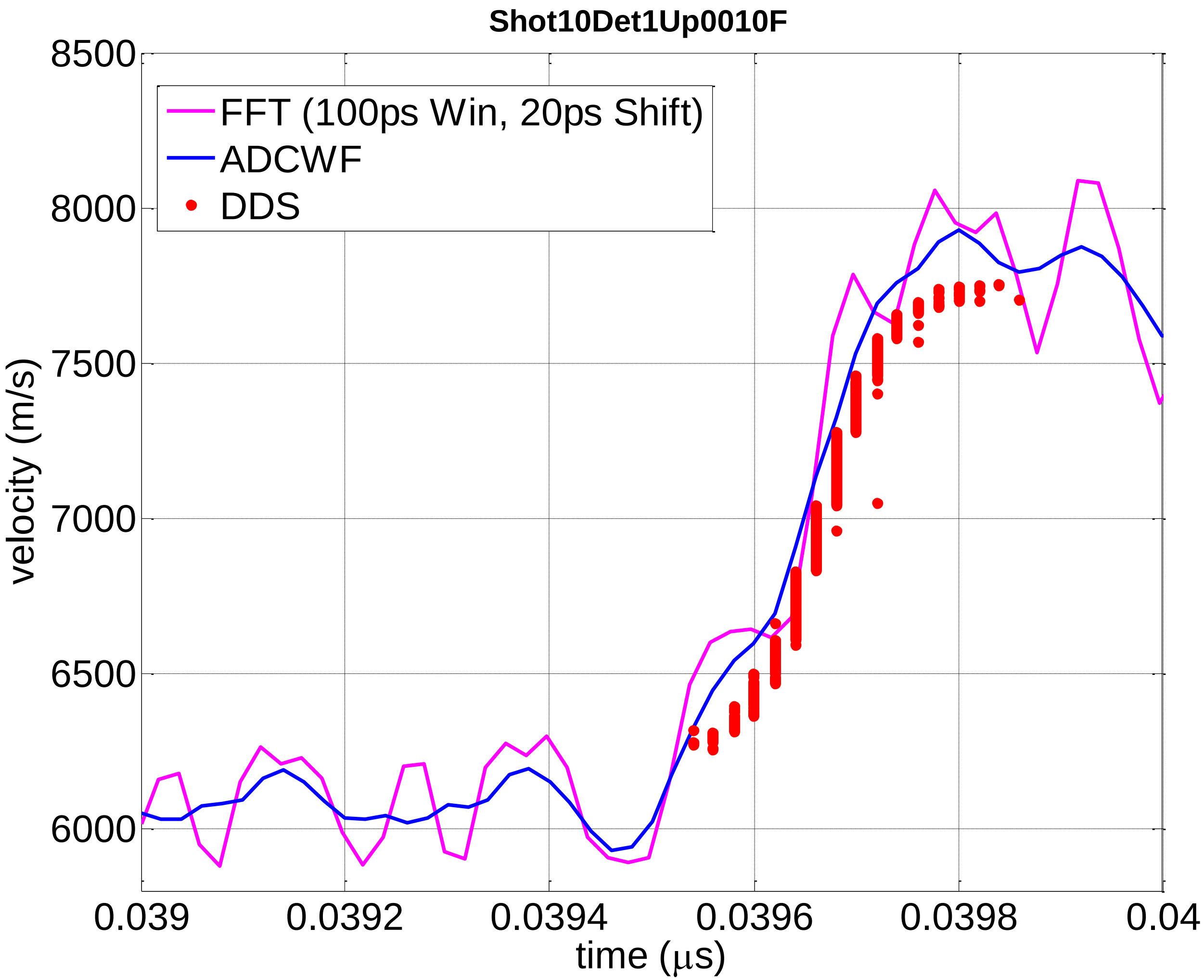

Appendix: Results