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Analysis of Optical Upshifted PDV Data

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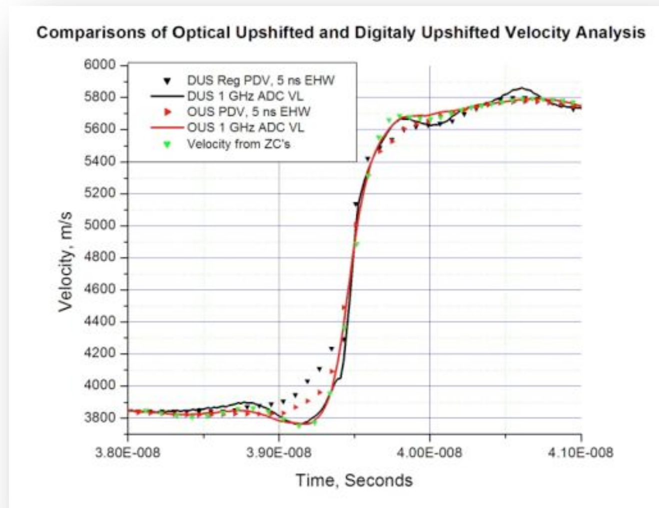
Related NSTec Site-Directed Research & Development Projects:

•2008: Many-point Velocimetry using Heterodyne Techniques

•2006: Dynamic Shock Source

•2006: Time Frequency Analysis



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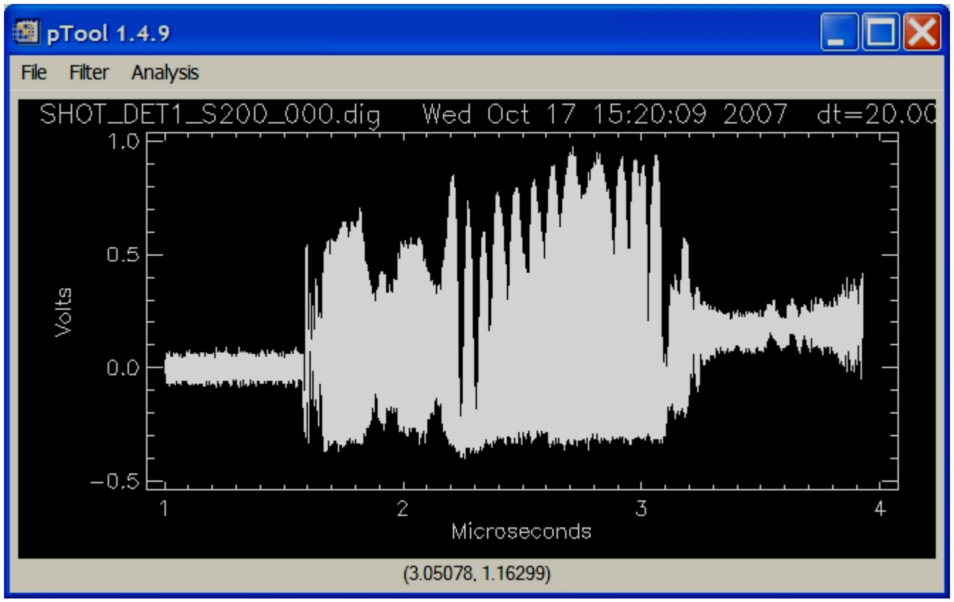
Outline

1. Analysis techniques (FFT, phase-based, zero-crossings)
2. Advantages of up-conversion (optical is just one type)
3. Optical upshift and experiments
4. OUS technique can isolate harmonics
5. More reliably extracts early time description in sharp velocity jumps
6. Can generate quadrature pair from single channel data which is the goal of more expensive triature/quadrature PDV systems
7. Improves time resolution of zero-crossing analysis
8. Summary

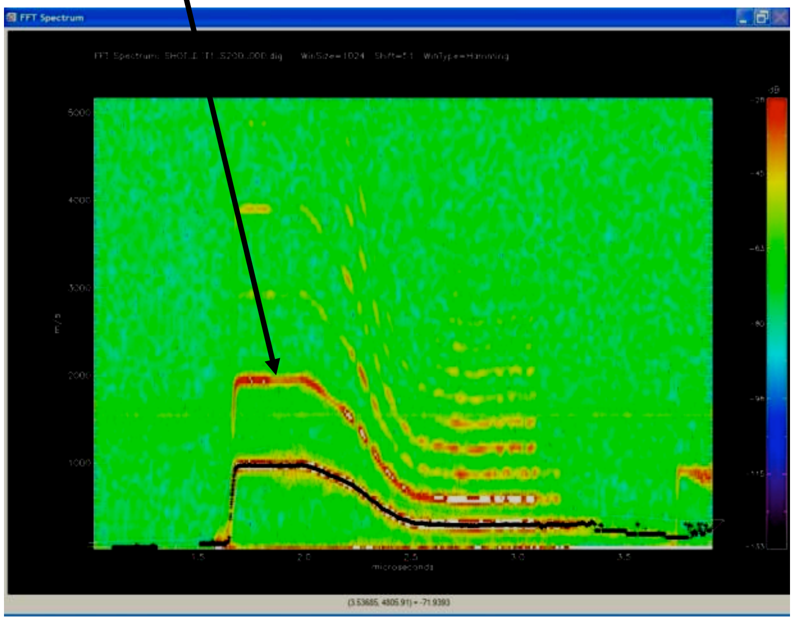
Analysis Techniques: FFT Spectrogram Analysis

$$S(t) = A(t)\cos(\phi(t)) + noise + harmonics + othersignals$$

$$\phi(t) = \phi_0 + 2\pi \int_{-\infty}^{t} f(t')dt', \qquad f(t) = \frac{v(t)}{\left(\frac{\lambda}{2}\right)}, \quad v(t) = velocity$$



Sample data



Spectrogram

FFT Analysis sacrifices **time resolution** for **frequency resolution**

Analysis Techniques: Phased-based

1. Phased-based techniques rely on extracting quadrature pair of signals, such as an in-phase signal, I(t), and out-of-phase (90°) signal, Q(t)

2. I(t) = cos(ωt+Φ) and Q(t) = –sin(ωt+Φ) would be such a pair.

3. Standard approach computes velocity as time derivative of continuously unfolded phase over some interval of N points:

$$V(\mathrm{t}) = \left(\frac{\lambda}{2}\right)\frac{1}{2\pi}\frac{d}{dt}\phi(t) \quad \text{where} \quad \phi(t) = \tan^{-1}\left(\frac{-Q(t)}{I(t)}\right)$$

5. VISAR−like (N = 2) at ***very high signal to noise:***

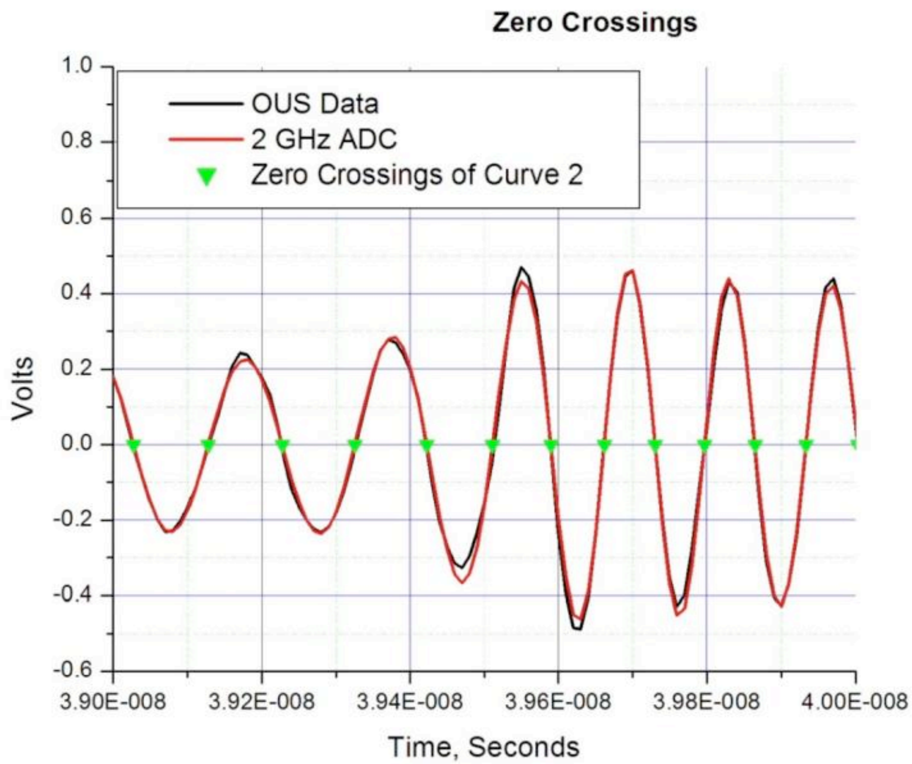
$$V_{VL}(t) = -\left(\frac{\lambda}{2}\right)\frac{1}{2\pi\Delta t}\underbrace{\tan^{-1}}_{-2\pi f\Delta t}\left(\frac{Q(n+1)I(n)-I(n+1)Q(n)}{I(n+1)I(n)+Q(n+1)Q(n)}\right)$$

6. Adaptive down conversion (ADC) can generate a quadrature pair at sufficiently high signal-to-noise ratios from a single channel PDV to use the VISAR-like analysis (see Appendix).

Analysis Techniques: Zero-crossings

The zero crossing analysis simply identifies the times at which a properly base-lined signal crosses the zero axis. Let $tz[i]$ be such a set of points in time. The time interval $P[i] = tz[i+1] - tz[i-1]$ would then be time period for one oscillation about $tz[i]$. We can define cycle averaged frequency at time $tz[i]$ as $f[i] = 1/P[i]$. The cycle averaged velocity is then

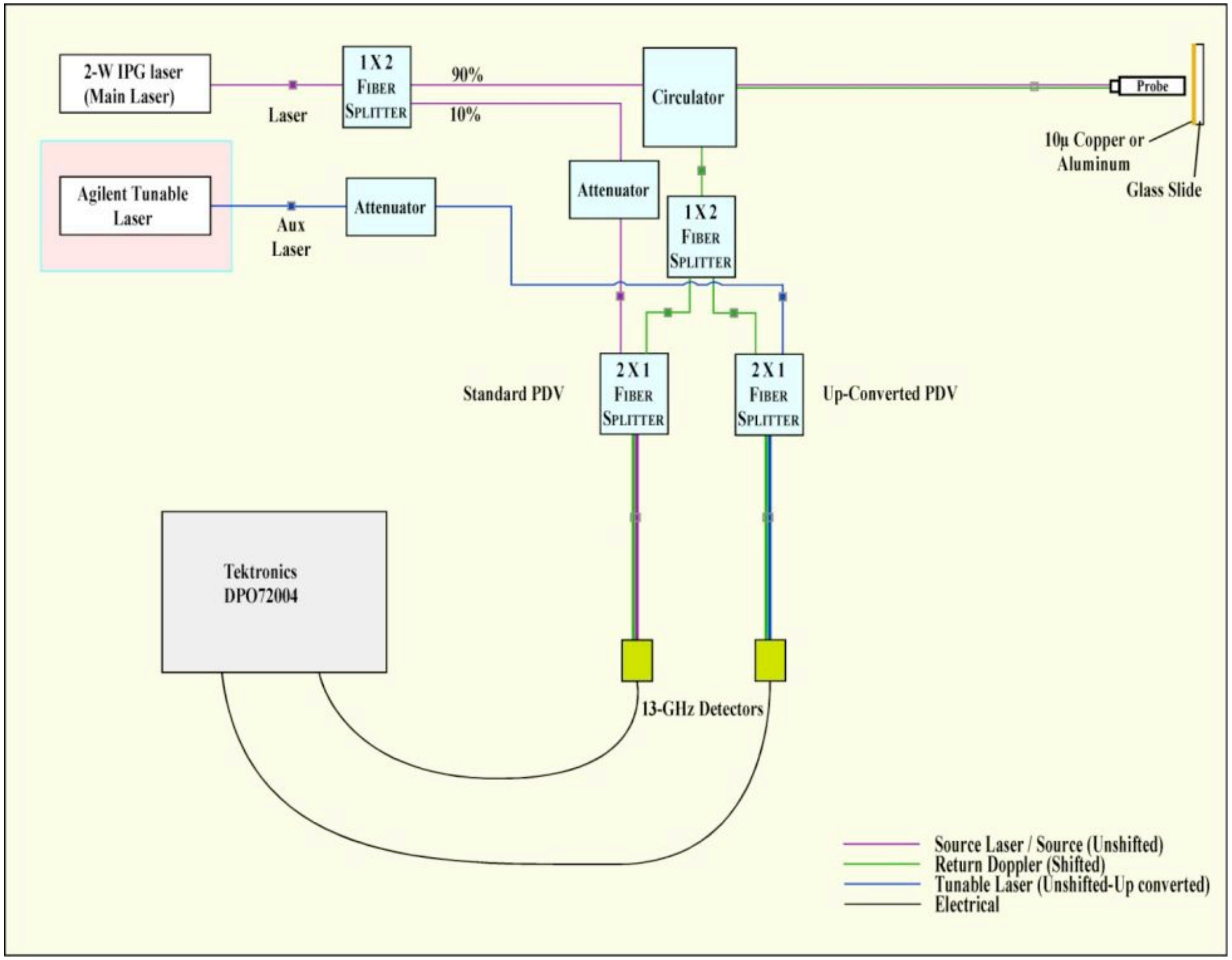
$$v[i] = \left(\frac{\lambda}{2}\right) / P[i].$$



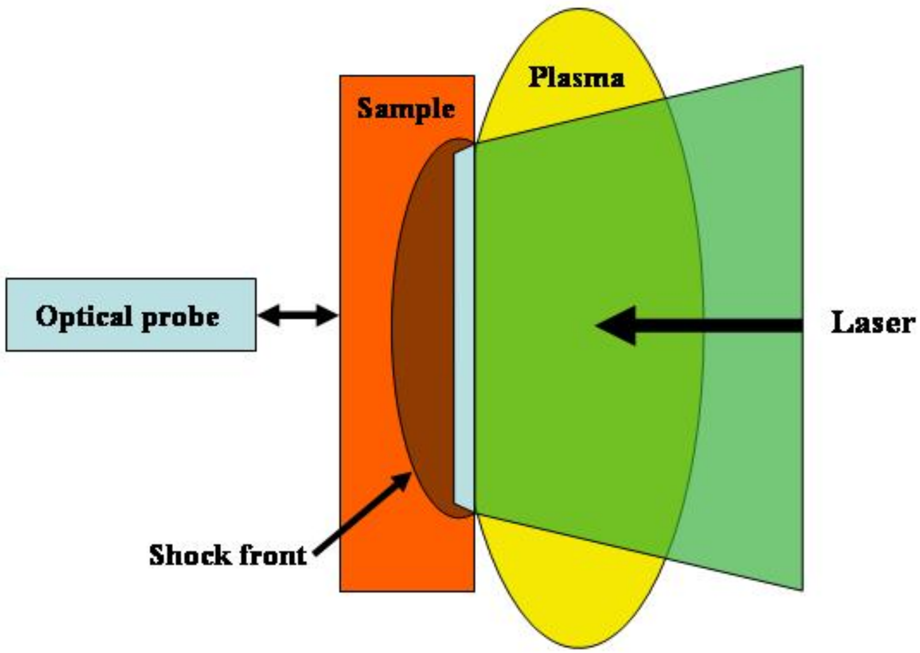
Dual PDV Optical Upshifted / Standard

Acquisition of standard PDV and optical upshifted PDV. Both PDV channels use the same reflected laser light. The up-shifted channel generated by mixing the reflected light with laser light from a tunable laser that is tuned so as to produce an apparent positive velocity even the velocity is 0.

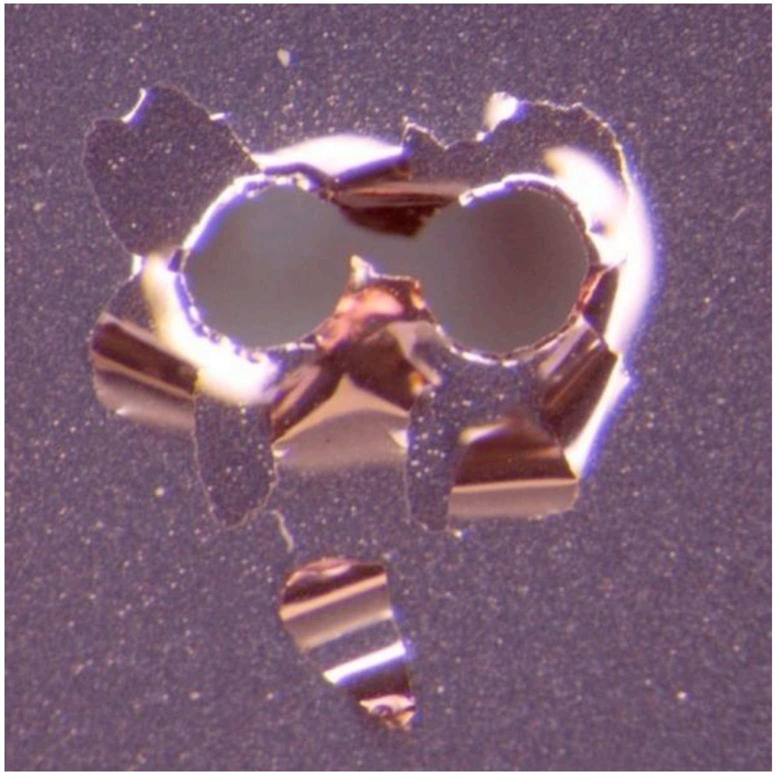
The optical up-shifted signal does not suffer from base line noise as with the standard PDV. Baseline noise can continue after breakout in standard PDV.



Principle of Laser Shock Source



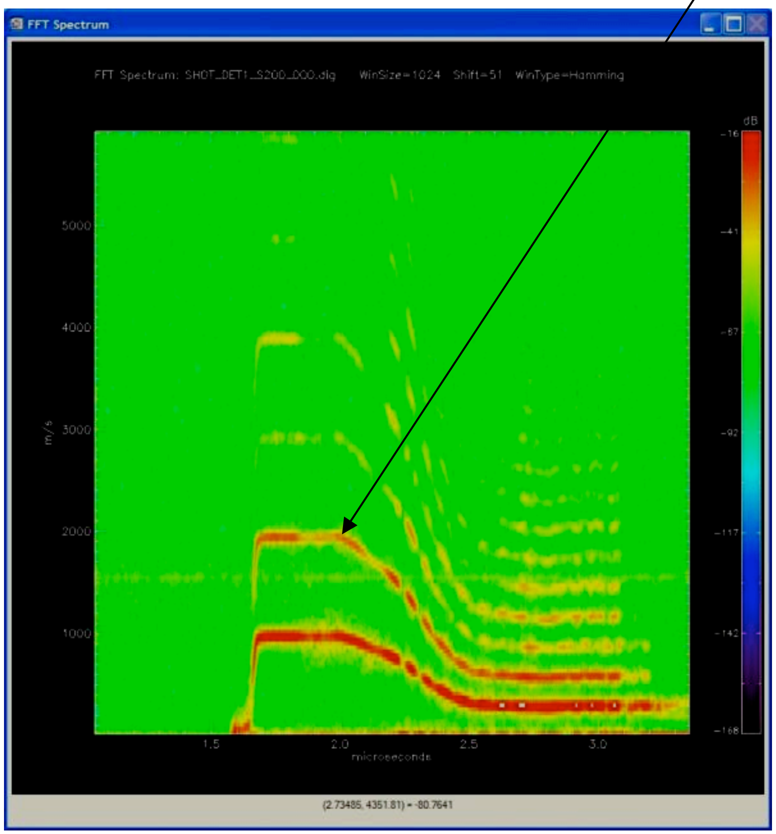
Generation of the shock

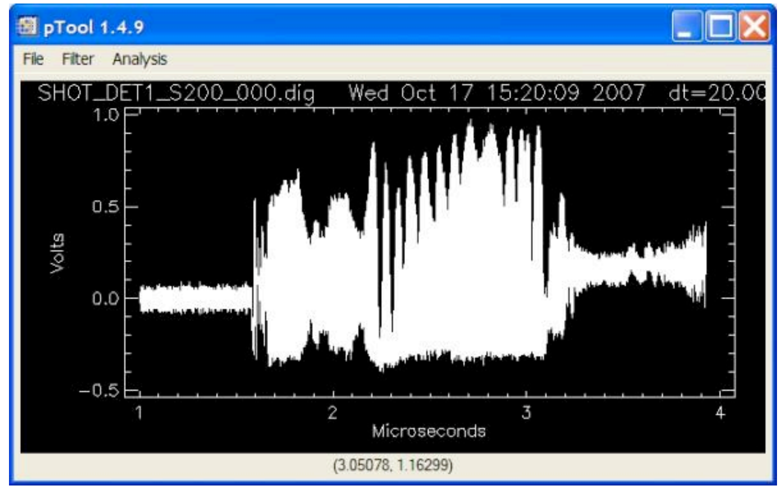


Result on 5 µm copper foil

Isolate Harmonics

Sample data shown at right, …



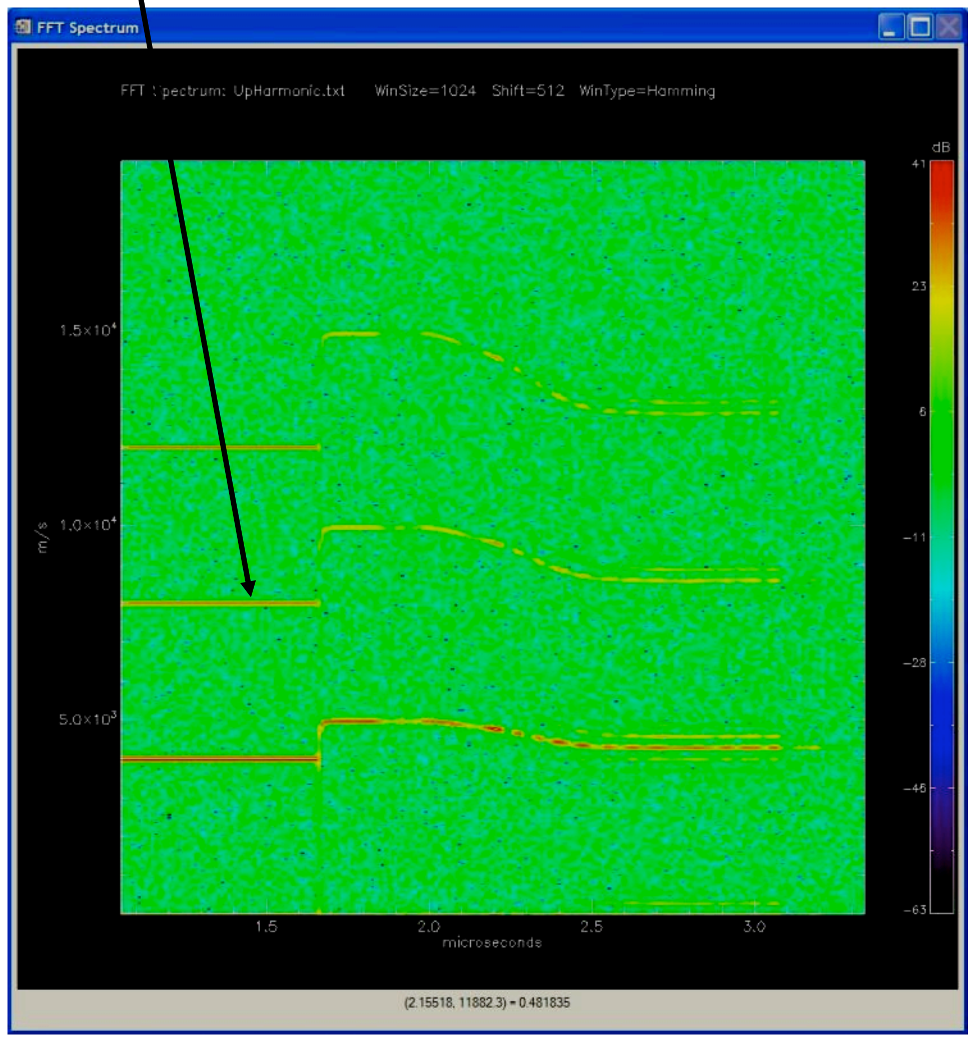


complete with harmonics. Frequency content of these harmonics overlap with the frequency range of the data of interest. Simple filtering is not sufficient to eliminate these harmonics for the phase-based analysis.

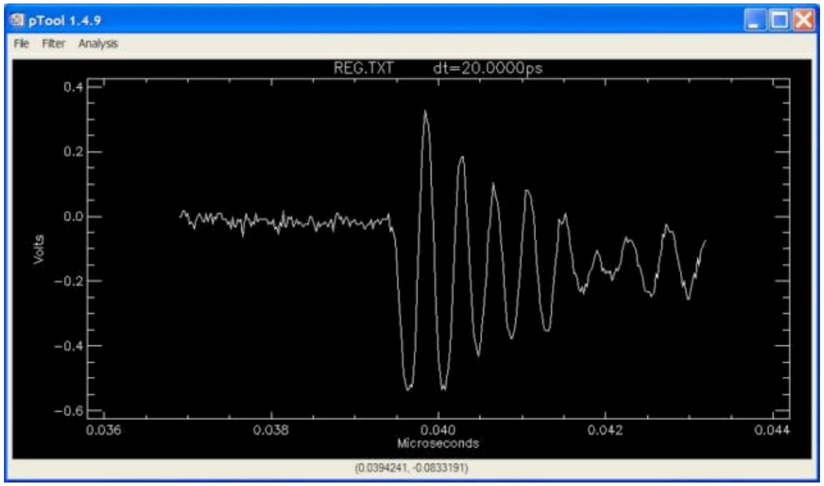
Isolate Harmonics

This FFT spectrogram was generated from simulated data using the relevant amplitude and velocity information from the previous sample signal. The difference is that in the simulation the velocity was up-shifted by 4 km/s.

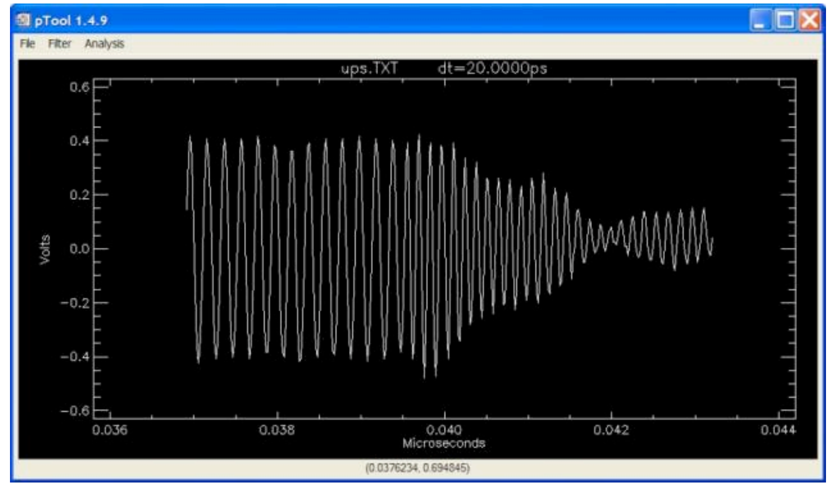
The simulation includes harmonics. The upshift of 4 km/s sufficiently isolates the fundamental signal, such that it can be easily extracted with simple filtering techniques.



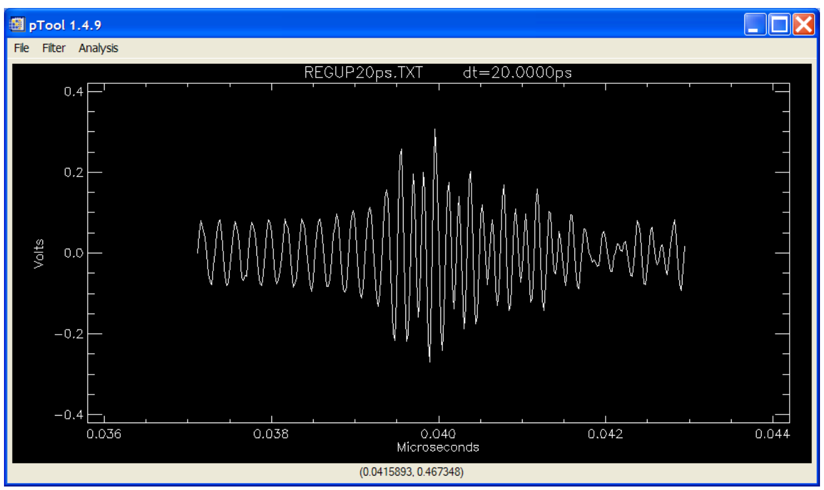
Extract Early Description in Sharp Velocity Jumps



Standard PDV Channel from Shot 11

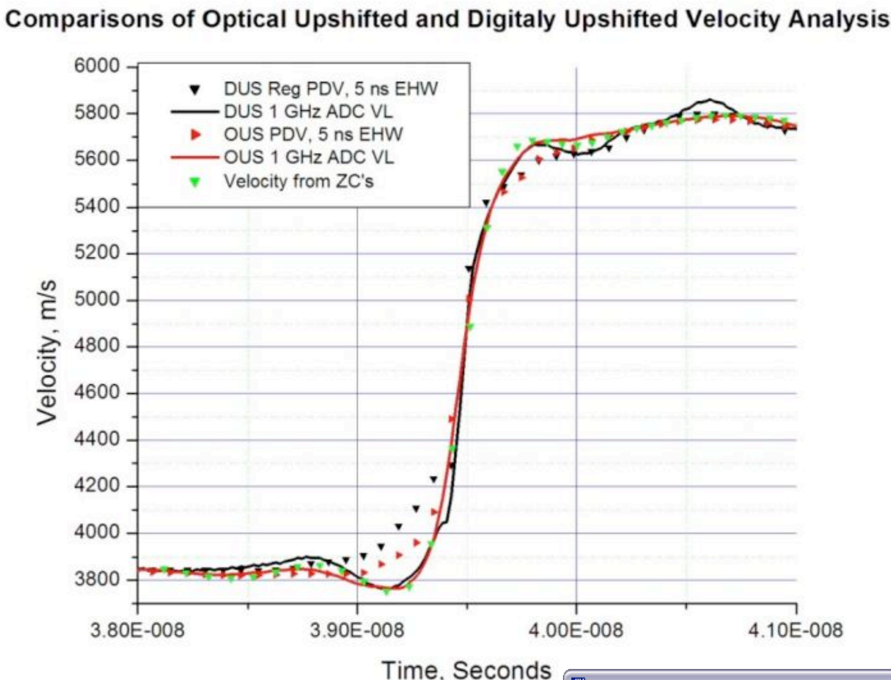


Optically upshifted channel from Shot 11



In a technique similar to digitally down-shifting the optically upshifted data, we can digitally upshift (DUS) the standard channel. The DUS waveform is shown at the left. The DUS of the baseline noise appears as a signal. The OUS and DUS data are analyzed next.

Extract Early Description in Sharp Velocity Jumps



The analysis results for the OUS data are smoother and show fewer artifacts than those of DUS data. In addition, the baseline result is based on true signal and provides opportunity for additional analysis. This additional analysis consists for forward modeling the velocity profile to a heavy-side step function = $V + \Delta v/(1 + \exp(-\Gamma(t\text{-}t_{mid})))$.

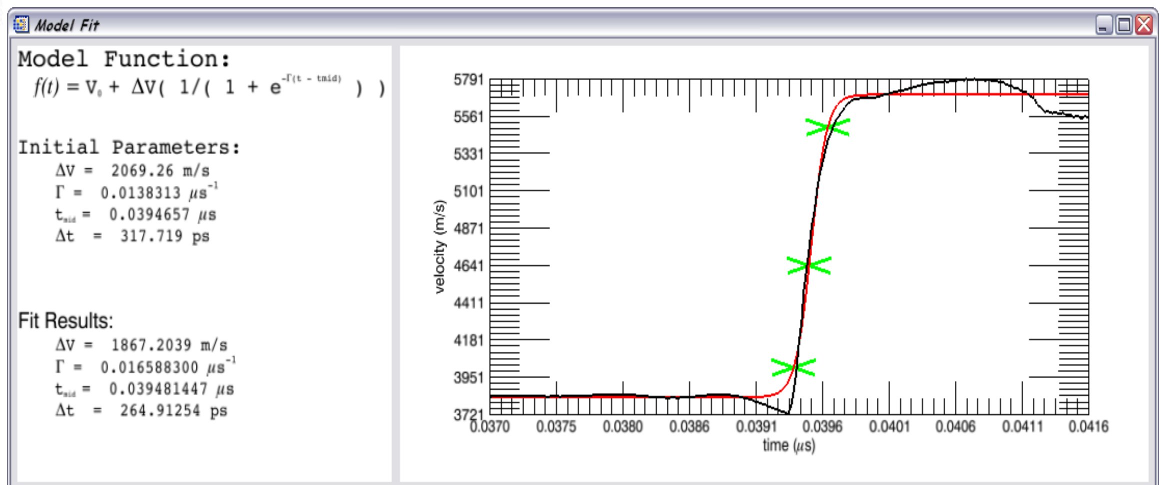
Analysis results:

Δv = 1867 m/s

Γ = 16.6 GHz

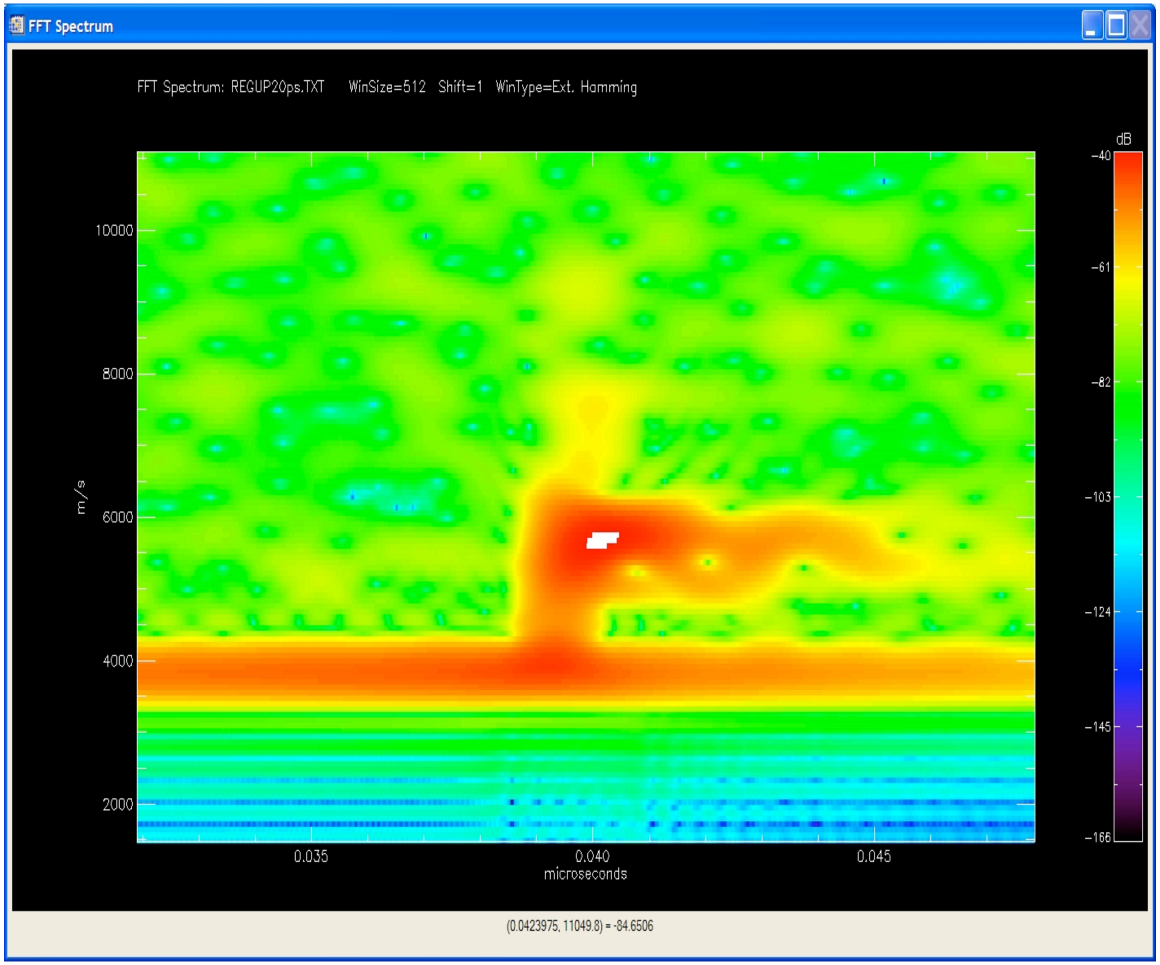
T_{mid} = 0.03948 ns

Δt (10-90% rise) = 265 ps



Extract Early Description in Sharp Velocity Jumps

Baseline noise can survive after breakout in DUS of standard standard PDV data. This baseline noise can interfere with the analysis.



Extract Early Description in Sharp Velocity Jumps

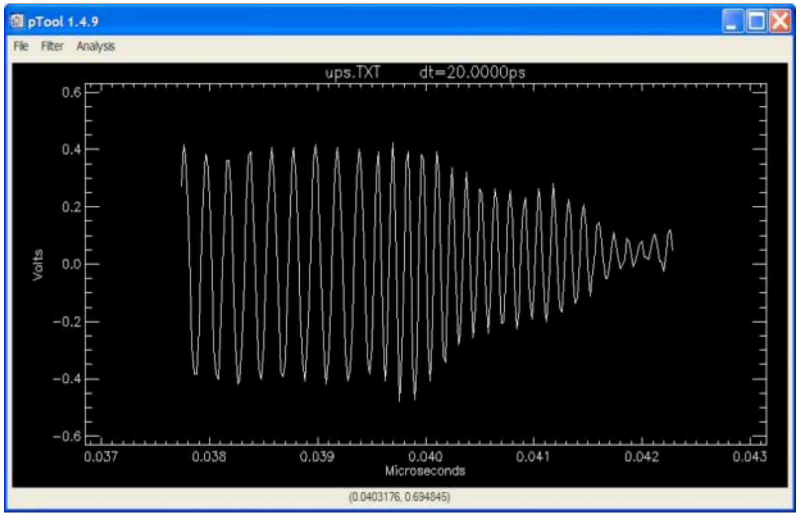
We have completed a similar analysis for numerous shots. The table at right summarizes the results. Average 10% to 90% rise times in the velocity profile are on order 250 ps.

The quantity $\frac{dV \times \Gamma}{4}$ is the maximum acceleration and is very large (on order of 8 10^{12} m/s^2), but the duration is roughly 0.25 ns, which results in a net velocity increase of 2,000 m/s.

To complete the analysis, we need to simulate data with these parameters and analyze. This work is in progress.

Shot Number	Base Velocity (m/s)	dV (m/s)	Γ (GHz)	10-90% risetime (ps)
Shot 1	2892	1931	16.7	263
Shot 2	2876	1929	14.6	301
Shot 3	3261	1936	19.9	221
Shot 4	3102	1649	20.2	218
Shot 5	3097	1758	13.9	315
Shot 6A	3639	1528	25.2	175
Shot 6B	3639	1792	22.6	191
Shot 7	3100	1750	23	318
Shot 8	3102	1835	18.9	233
Shot 9A	3099	1518	16.3	270
Shot 9B	3091	1590	26	169
Shot 9C	3099	1639	15	292
Shot 10	1092	1596	16.9	260
Shot 11	3827	1867	16.9	261

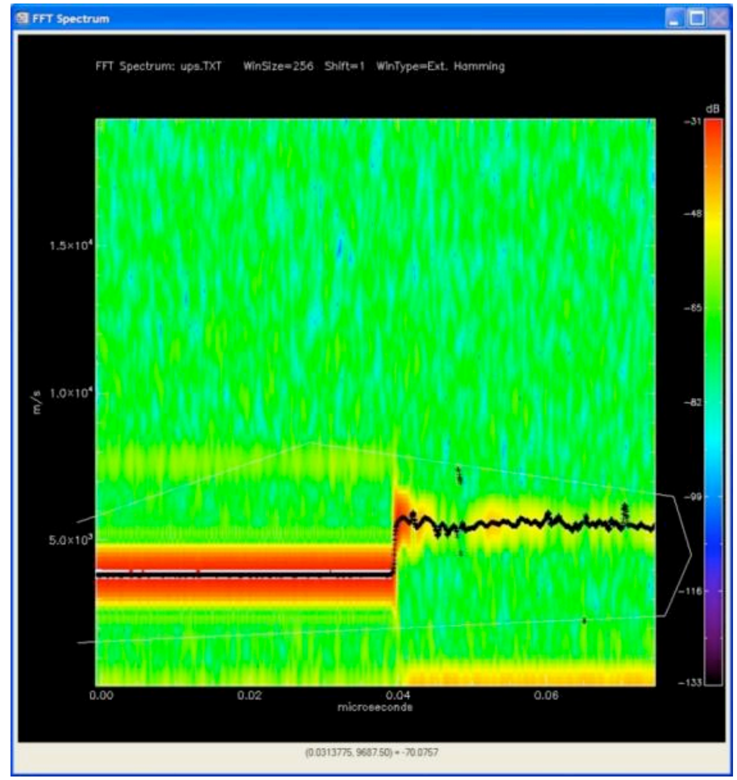
Generate Quadrature Pair from Single Channel Data



Optical up-shifted data, Shot 11, June 24.

FFT spectrogram shows signal,

$S(t) = A(t)\cos(\Phi(t))$.



Base velocity is 3827 m/s. We can convert to frequency, f_b, generate mixing functions $\cos(2\pi f_b\, t)$ and $\sin(2\pi f_b\, t)$ and multiply the data with these mixing functions. With some filtering steps, we can down-shift a quadrature pair of signals.

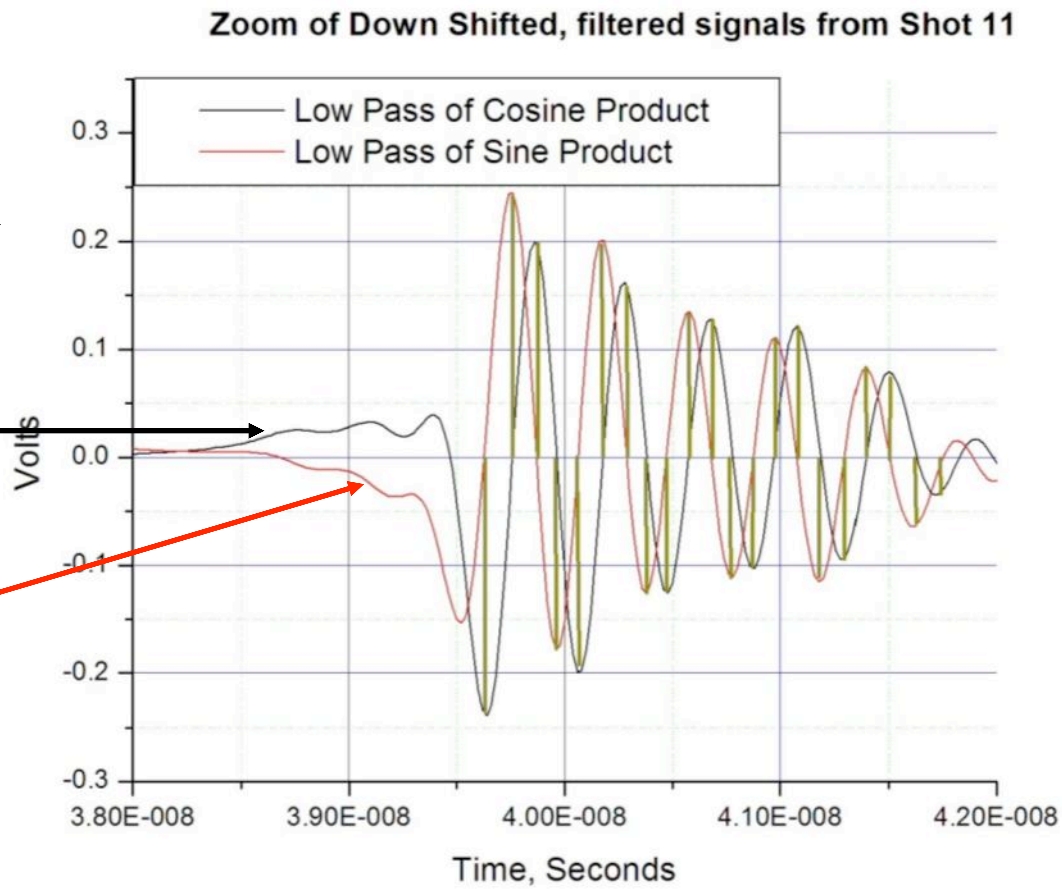
Generate Quadrature Pair from Single Channel Data

The down-shifted quadrature pair of signals are plotted at right. Low Pass of Cosine Product refers to low pass filter of data multiplied by $\cos(2\pi f_b\ t)$ or

$A(t)\cos(\Phi(t)-2\pi f_b\ t)\ /2$,

and similarly for the Low Pass of Sine Product or

$A(t)\sin(\Phi(t)-2\pi f_b\ t)/2$.

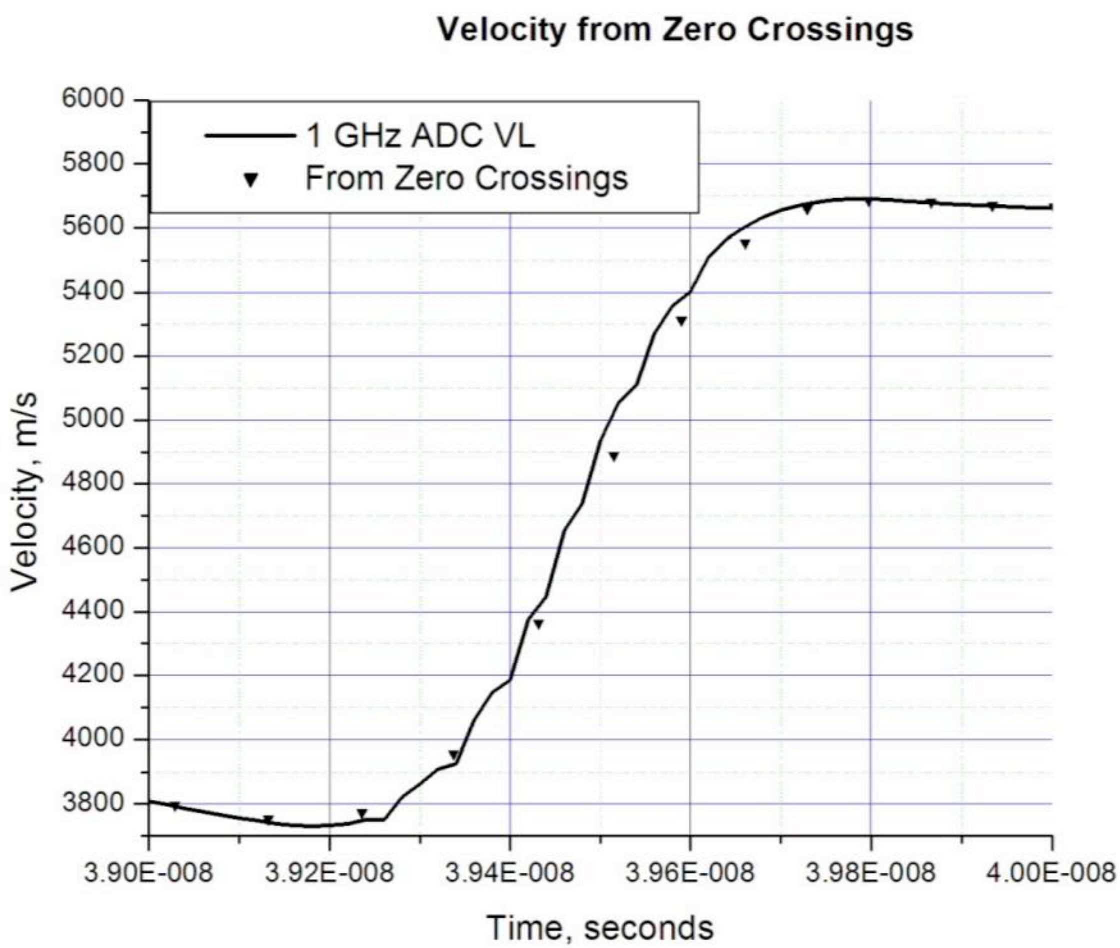


Because of rumble at breakout, both signals also need to be high-pass filtered, in this case, at 250 MHz. The zero crossings of one signal correlate with the zero crossings of the other signal.

Analysis Techniques: Zero-crossings

Thirteen zero crossings within 1 ns, or roughly every 80 ps (or 60 ps at higher velocity), versus 150 ps for zero crossings for standard PDV data.

These results are computed for the zero crossings of the in-phase signal I (slide 5). If we include the zero crossing analysis for the out-of-phase signal Q, than time resolution can be increased to 40 (or 30 ps at higher velocity). But with single channel PDV, we cannot compare Q with data.



Conclusion

1. OUS technique can isolate harmonics in OUS PDV data.
2. OUS PDV data provide a strong baseline for an early time description in sharp velocity jumps. DUS PDV data provide baseline based on noise and do not necessarily transition smoothly into the shock velocity profile because baseline noise can continue after breakout which can interfere with analysis. We can analyze OUS velocity profiles to characterize PDV probe performance.
3. Quadrature in-phase and out-of-phase signals can be extracted from single-channel OUS PDV data. (Can do same for DUS single PDV channel data or with ADC analysis).
4. OUS PDV data improve time resolution of zero-crossing analysis. This can also be true of DUS PDV data.

Appendix: Adaptive Down Conversion (ADC)

1. Start with a first order estimate for velocity, $v^{(0)}(t)$, such as that might be obtained from FFT analysis.
2. Convert first order velocity to frequency, $f^{(0)}(t) = \dfrac{v^{(0)}(t)}{\left(\dfrac{\lambda}{2}\right)}$.
3. Integrate frequency to generate phase, $\phi^{(0)}(t) = 2\pi \int_{-\infty}^{t} f^{(0)}(t')dt'.$
4. Generate mixing functions, $\cos(\phi^{(0)}(t))$ and $\sin(\phi^{(0)}(t)).$
5. Multiply the data, D(t), by the mixing functions:

$$PC(t) = \cos(\phi^{(0)}(t)) \times D(t) = \frac{A(t)}{2}\{\cos(\phi(t) - \phi^{(0)}(t)) + \cos(\phi(t) + \phi^{(0)}(t))\},$$

$$PS(t) = \sin(\phi^{(0)}(t)) \times D(t) = \frac{A(t)}{2}\{\sin(\phi(t) - \phi^{(0)}(t)) + \sin(\phi(t) + \phi^{(0)}(t))\}.$$

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

$$LC(\phi(t) - \phi^{(0)}(t)) = \frac{A(t)}{2}\cos(\phi(t) - \phi^{(0)}(t)) \qquad LS(\phi(t) - \phi^{(0)}(t)) = \frac{A(t)}{2}\sin(\phi(t) - \phi^{(0)}(t))$$

ADC (contd)

5. Generate I as

$$I(t) = 2\times\left[LC(\phi(t)-\phi^{(0)}(t))\times\cos(\phi^{(0)}(t)) - LS(\phi(t)-\phi^{(0)}(t))\times\sin(\phi^{(0)}(t))\right]$$

7. Generate Q as

$$Q(t) = 2\times\left[LS(\phi(t)-\phi^{(0)}(t))\times\cos(\phi^{(0)}(t)) + LC(\phi(t)-\phi^{(0)}(t))\times\sin(\phi^{(0)}(t))\right]$$

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

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

VISAR-like Velocity

If we consider the relationships at the right, variations in amplitude cancel in the algebra and do not matter.

$$I(n) = \cos(\phi(n)).$$
$$Q(n) = -\sin(\phi(n)).$$
$$I(n+1) = \cos(\phi(n+1)).$$
$$Q(n+1) = -\sin(\phi(n+1)).$$

Then these relationships follow from simple trigonometry.

$$Q(n+1)I(n) - I(n+1)Q(n) = -\sin(\phi(n+1)-\phi(n)) = -\sin(2\pi f\Delta t).$$
$$I(n+1)I(n) + Q(n+1)Q(n) = \cos(\phi(n+1)-\phi(n)) = \cos(2\pi f\Delta t).$$

The velocity between sample points is calculated as:

$-2\pi f\Delta t$

$$\text{VISAR-like} \quad V_{VL}(t) = -\left(\frac{\lambda}{2}\right)\frac{1}{2\pi\Delta t}\tan^{-1}\left(\frac{Q(n+1)I(n) - I(n+1)Q(n)}{I(n+1)I(n) + Q(n+1)Q(n)}\right).$$

It is called VISAR-like because we calculate this velocity directly as the arctangent of a ratio, just like VISAR (without missed fringes).