PDV in a Railgun

The Institute for Advanced Technology
The University of Texas at Austin

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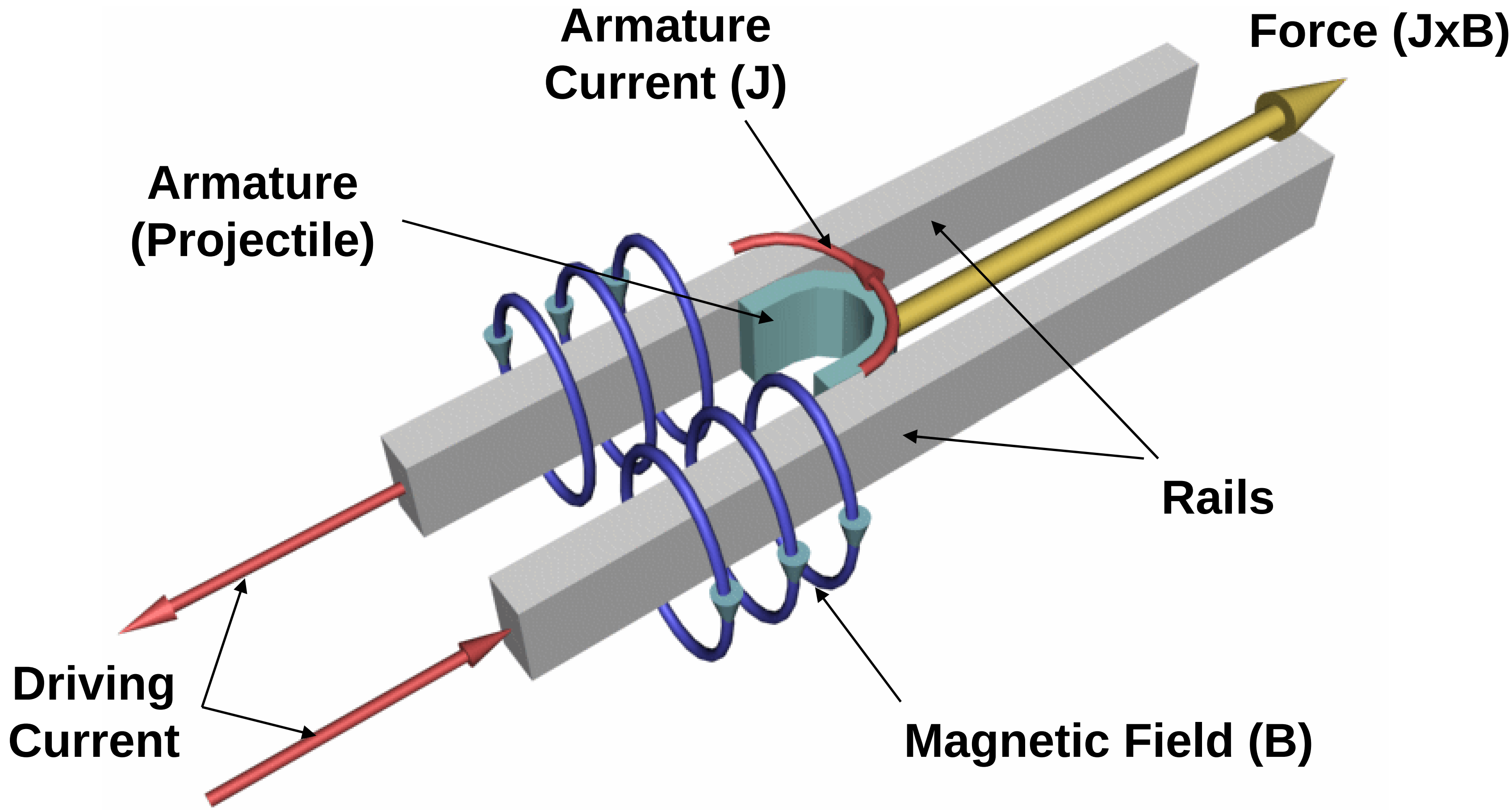
2nd Annual PDV Workshop
Aug 16-17, 2007
Lawrence Livermore National Laboratory

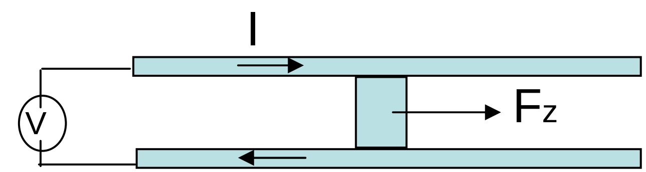
Electromagnetic Launcher



The current flowing in the rails causes a magnetic field which interacts with the current in the armature, generating a Lorentz (JxB) force.

Propulsion Force

Energy Balance: $$\int_0^t VIdt = \int dE_m + \int_0^t RI^2 dt + \int F_z dz$$



Faraday's Law: $$V = RI + \frac{\partial \phi}{\partial t}$$

=> $$E_m = \int I d\phi - \int F_z dz$$

=> $$F_z = -\left.\frac{\partial E_m}{\partial z}\right|_{\phi} ; \text{ and I} = \left.\frac{\partial E_m}{\partial \phi}\right|_z$$

=> $$F_z = -\frac{\partial}{\partial z}\left(\frac{\phi^2}{2L}\right) = \frac{1}{2}\frac{\partial L}{\partial z} I^2$$

This is a geometric parameter.

Railgun Equations

- Propulsion force:

$$F = ma = \tfrac{1}{2} L' I^2 - F_f$$

- L' is the "inductance gradient", a geometric constant, and is around 0.5 μH/m

$$F_f = \tfrac{1}{2} L' I^2 - m\dot{v}$$

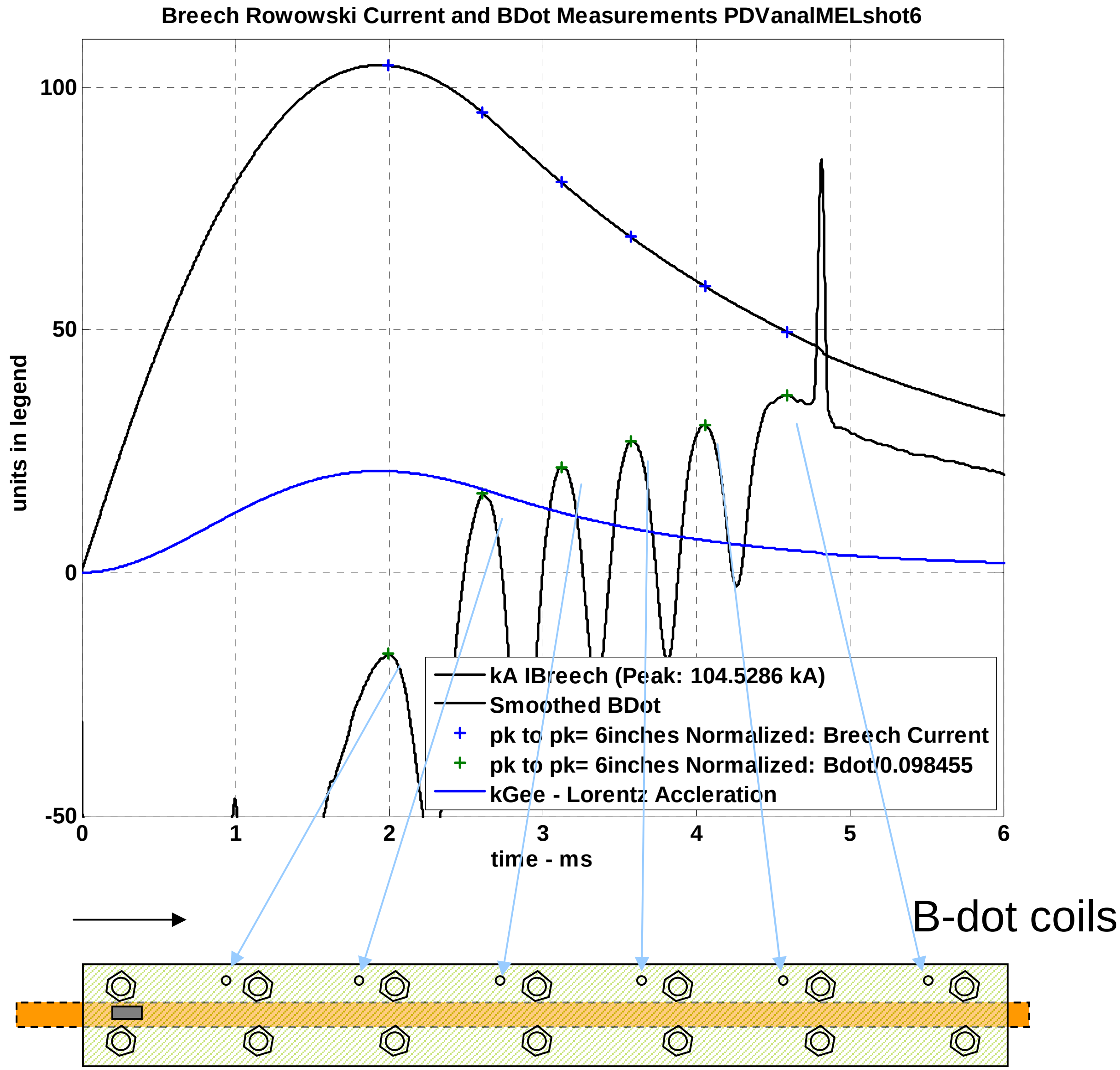
Measured with PDV method

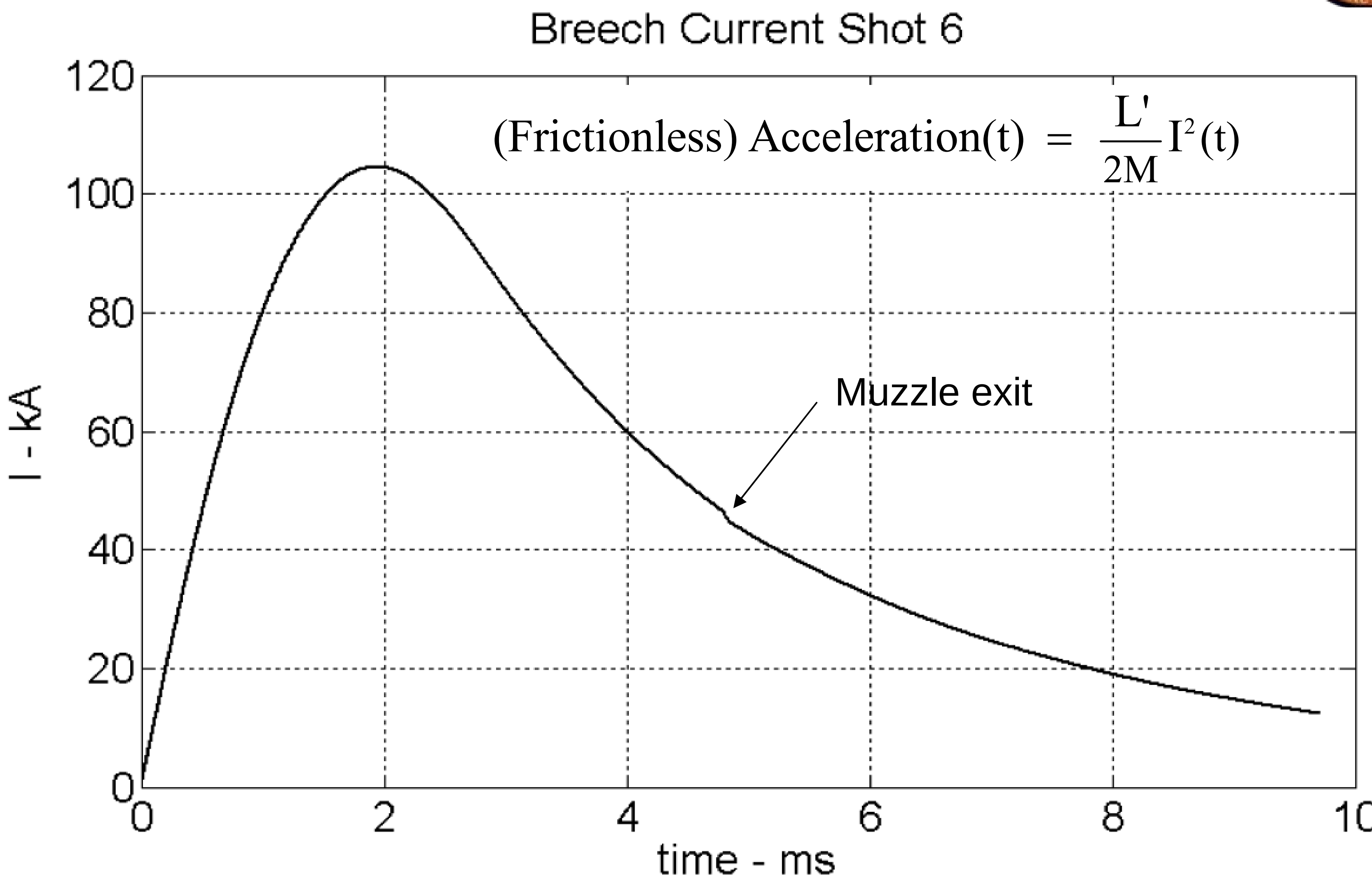
Measured with Pearson coil

Why is Friction Measurement Important?

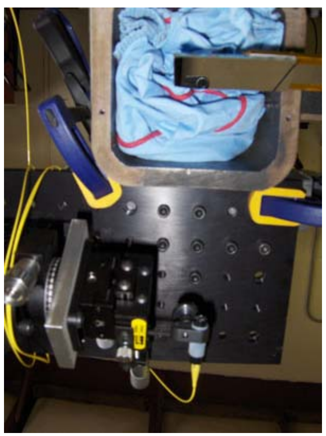
- The start-up region requires initial external contact pressure to carry current.
- Due to long residence time of the armature at the start-up region, abnormal damage occurs to both rail and armature.
- Role of lubrication in the interface is under study.
- Accurate measurement of the initial motion is extremely important for studying lubrication effects.

Typical measurement from B-Dot probes

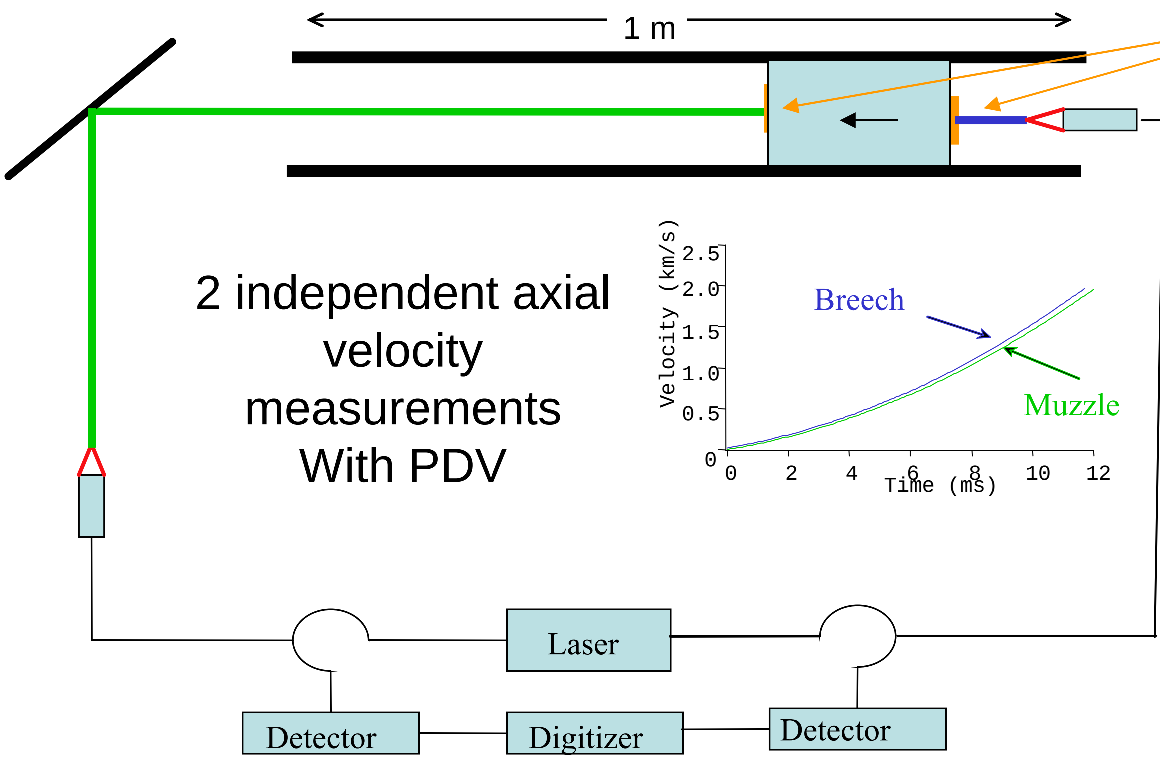



Breech Current Shot 6
(Frictionless) Acceleration(t) = $\frac{L'}{2M} I^2(t)$
Muzzle exit
I - kA
time - ms
120
100
80
60
40
20
0
0
2
4
6
8
10

Axial Velocity Measurements with PDV on 1 m Railgun at IAT

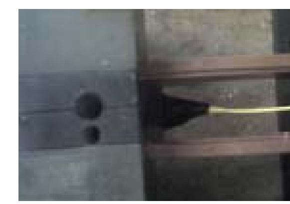


Muzzle Probe



3M µRetroReflective Surfaces

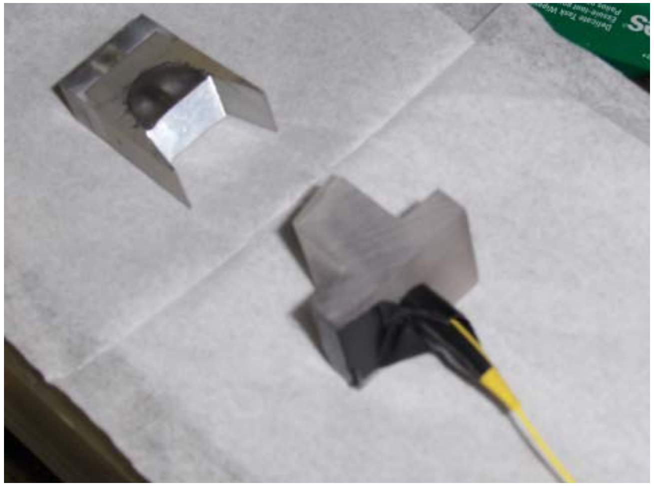
Beech Probe

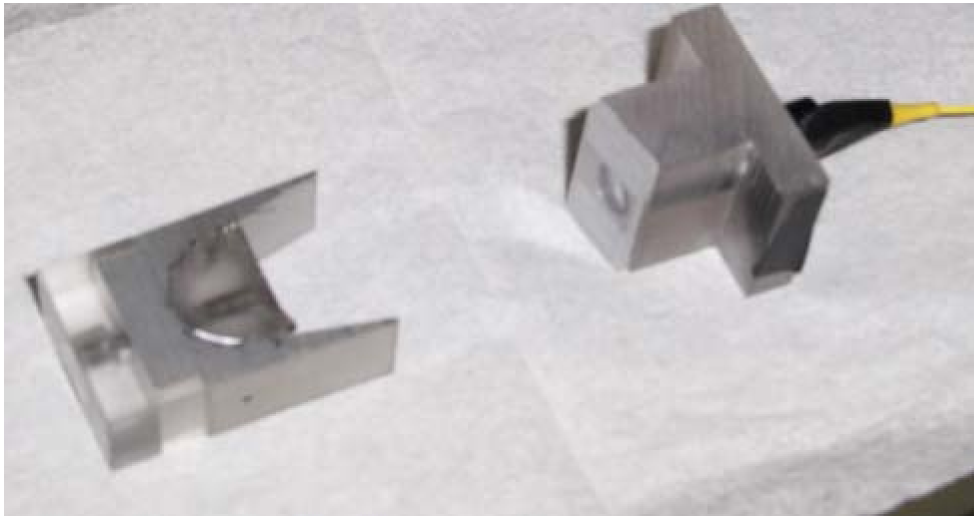


2 independent axial velocity measurements With PDV

$$v_i = 0.775 \frac{\text{m/s}}{\text{MHz}} \Delta f_i$$

Breech Probe &
Leading & Trailing Edges of Launch Package



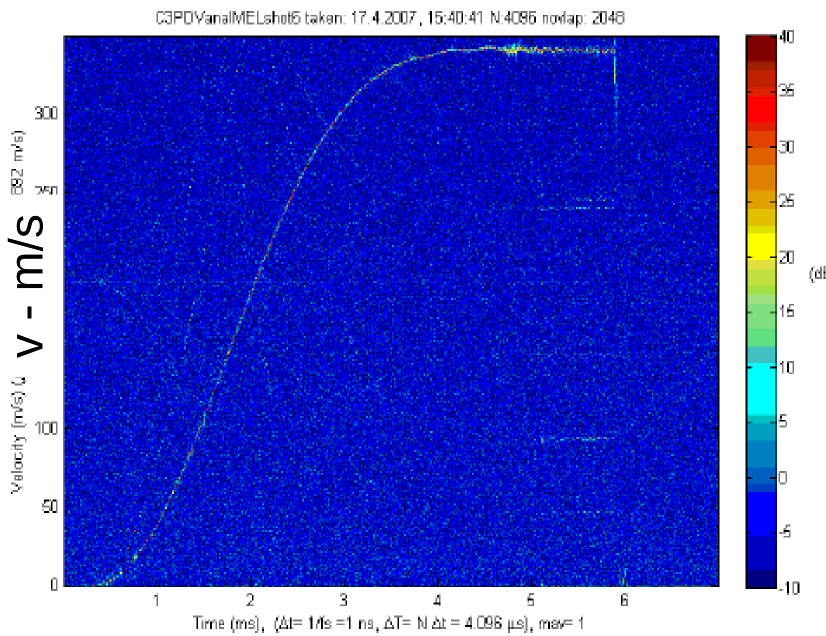


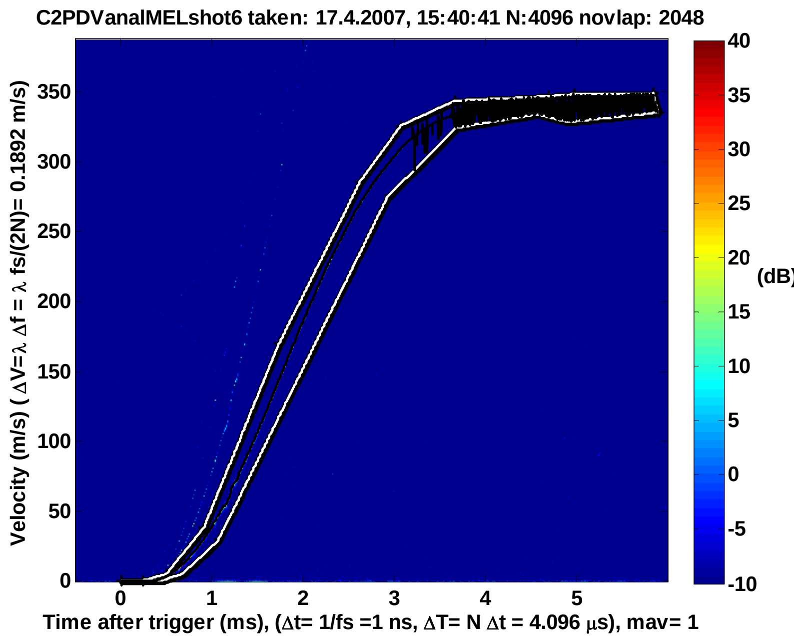
Breech & Muzzle Probe Spectrograms 1 m Railgun

$$|s(\Delta f,t)|^2 = S(\Delta f,t) \rightarrow S(v,t) \qquad v = 0.775 \frac{\text{m/s}}{\text{MHz}} \Delta f_i$$

Muzzle Probe

Breech Probe (bracketed)





t (ms)

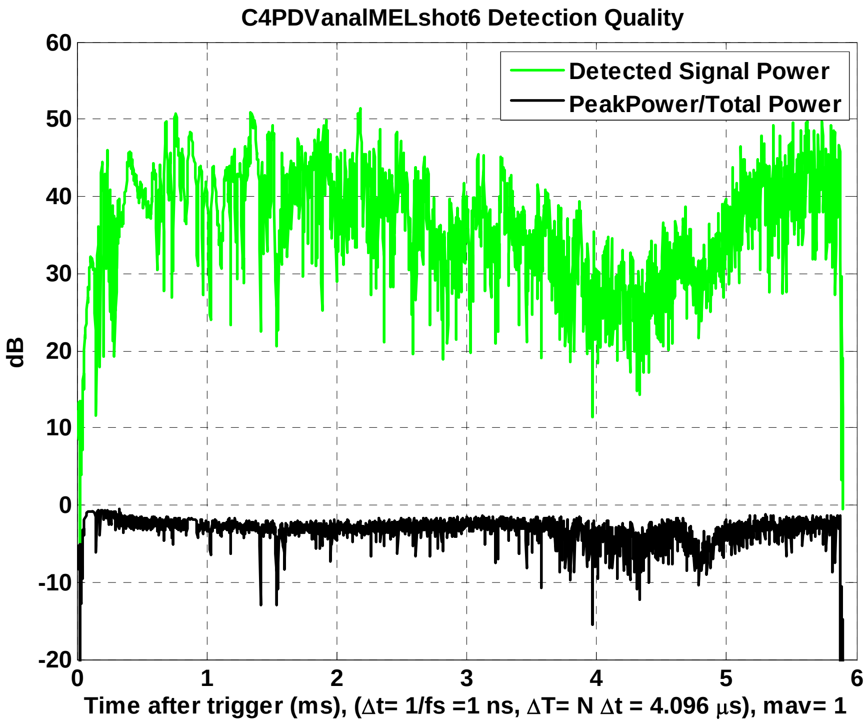
t (ms)

Signal S(t) and S(t) /N(t)

$$S(t) = \max_k \left| s\left(\Delta f_k, t\right) \right|^2 = \max_k \left| s\left(v_k, t\right) \right|^2$$

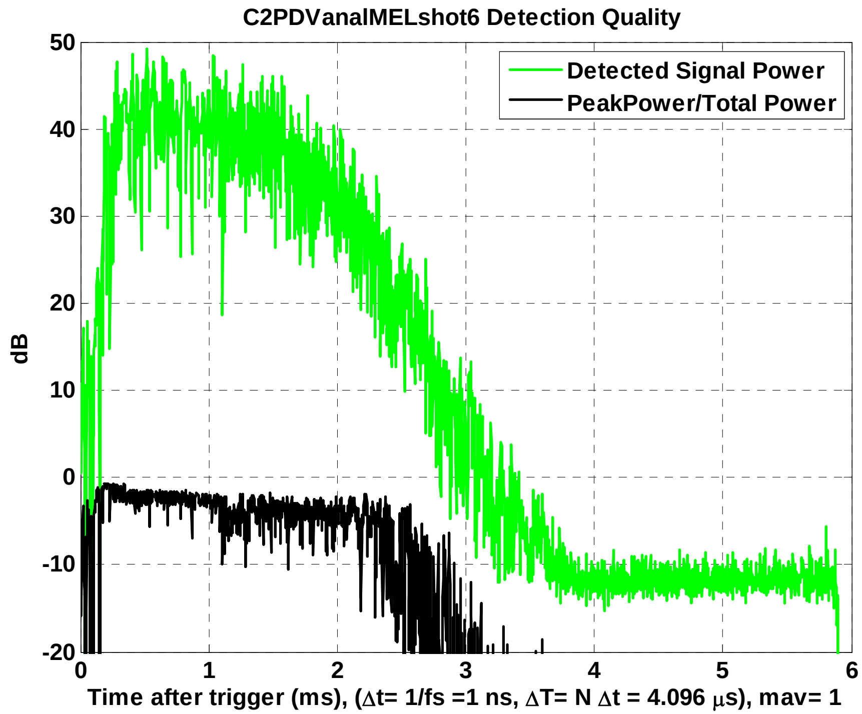
$$S(t)/N(t) \cong \frac{S(t)}{\sum_{k=1}^{2048} \left| s\left(v_k, t\right) \right|^2 - S(t)}$$

Muzzle Probe



t (ms)

Breech Probe

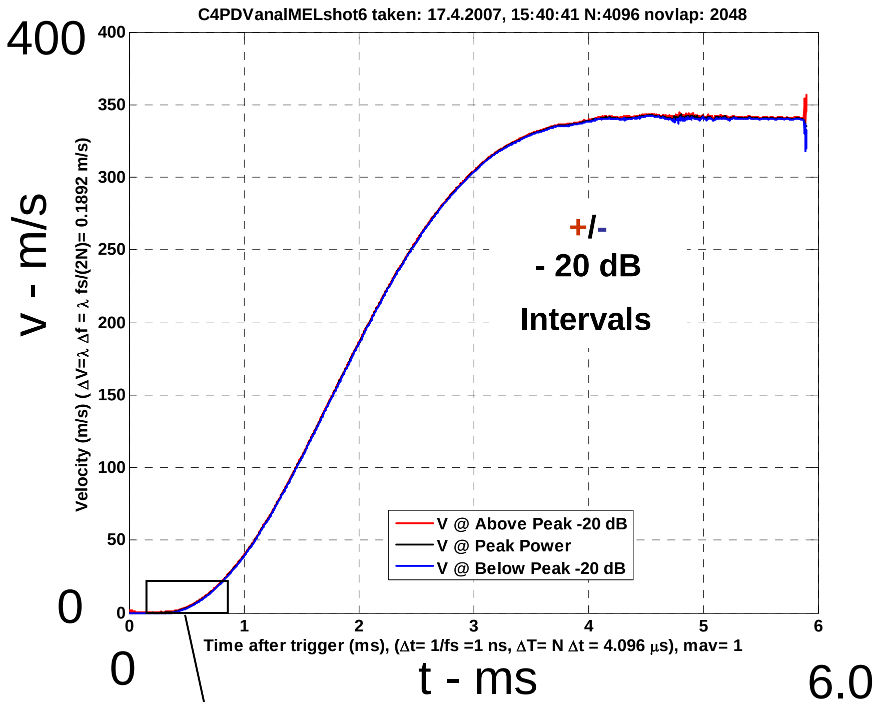


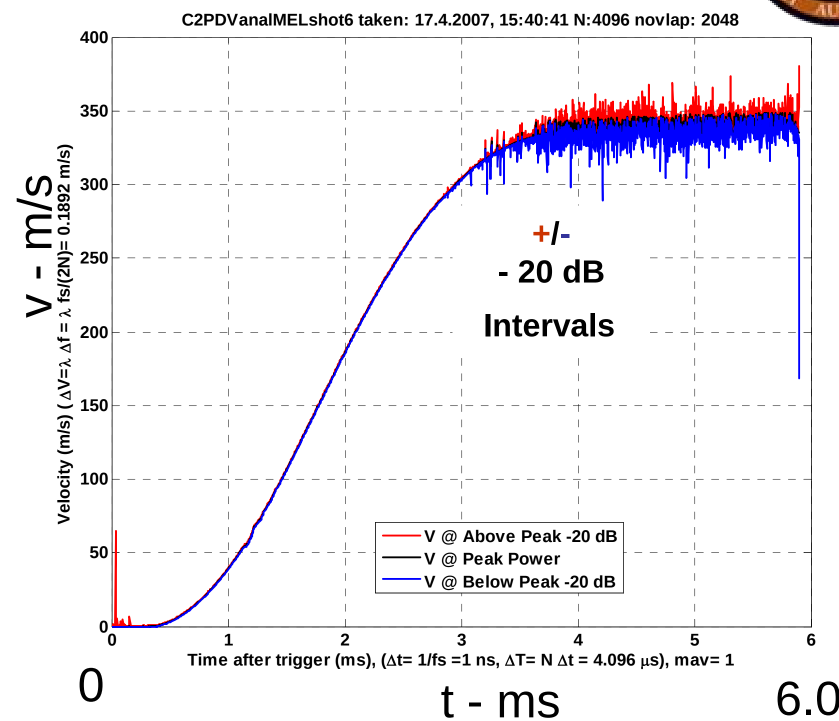
t (ms)

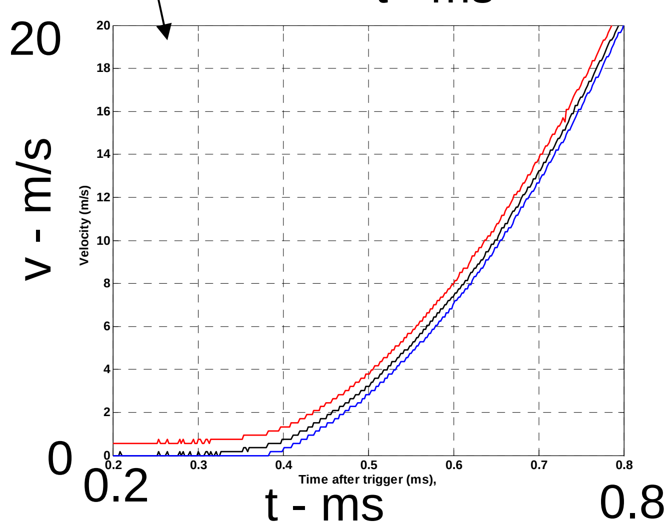
Velocity Statistics

Muzzle Probe ↓

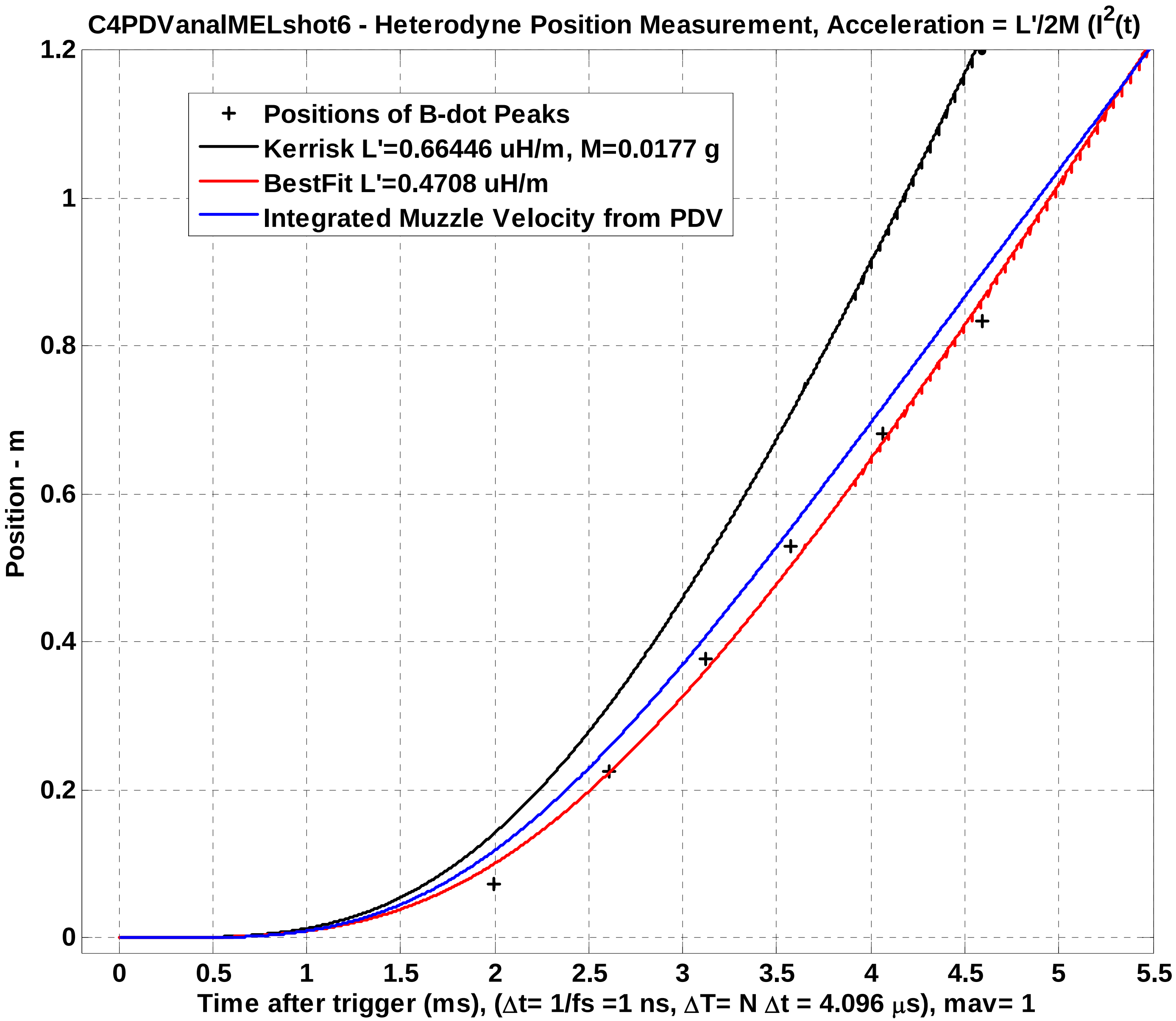
Breech Probe ↓



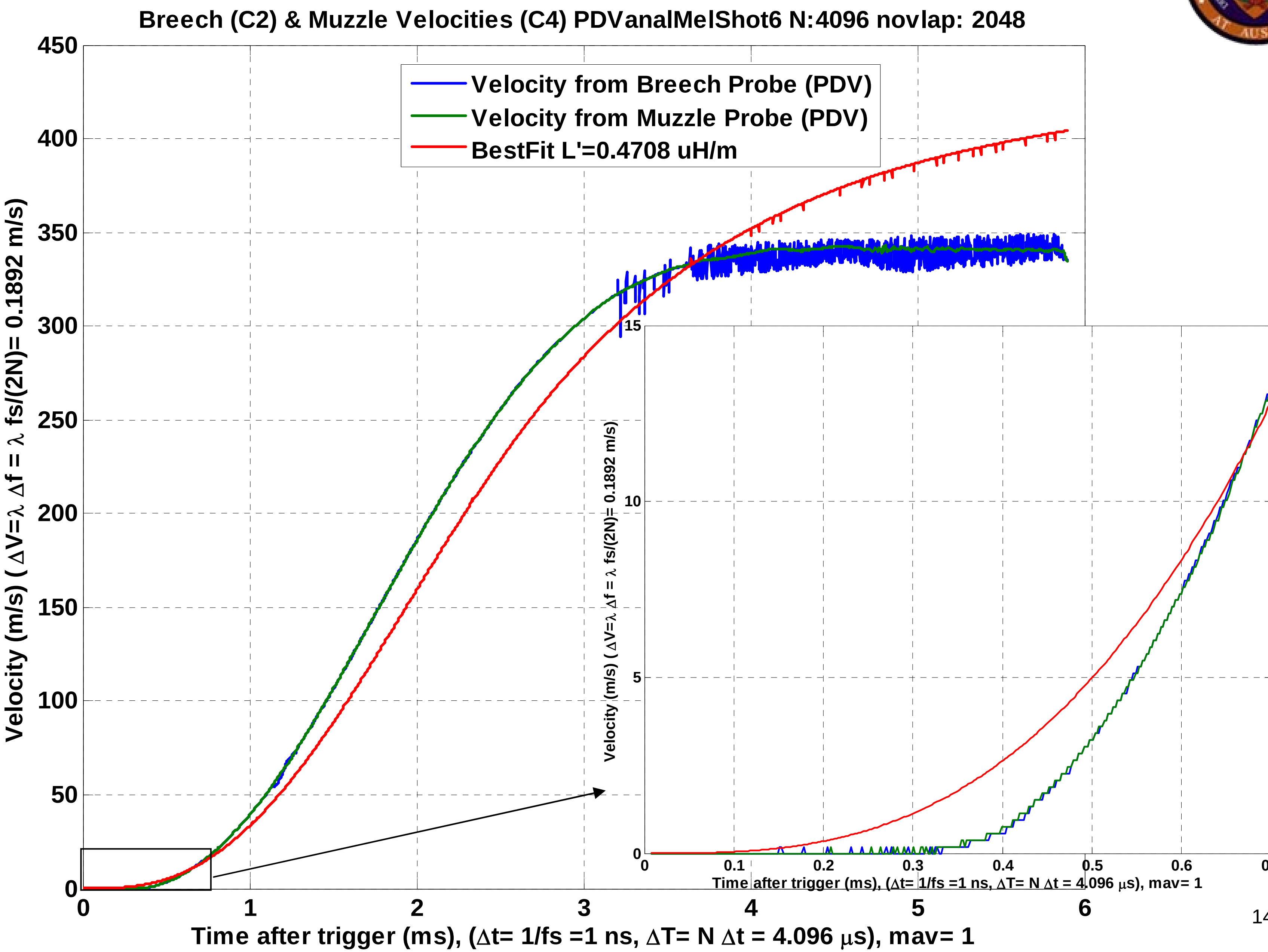




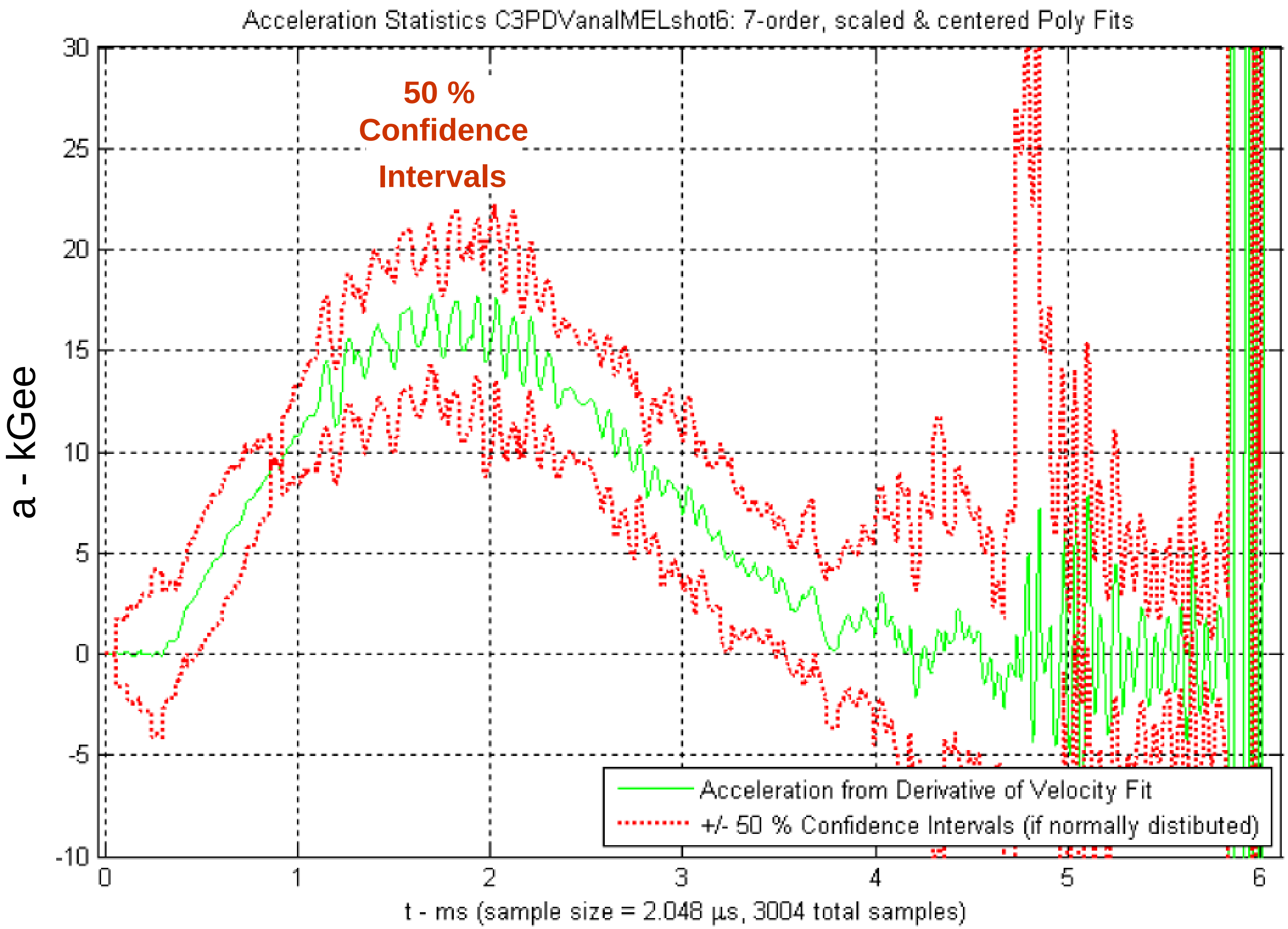
Axial Position from PDV and B-Dot



Breech and Muzzle PDV Velocities

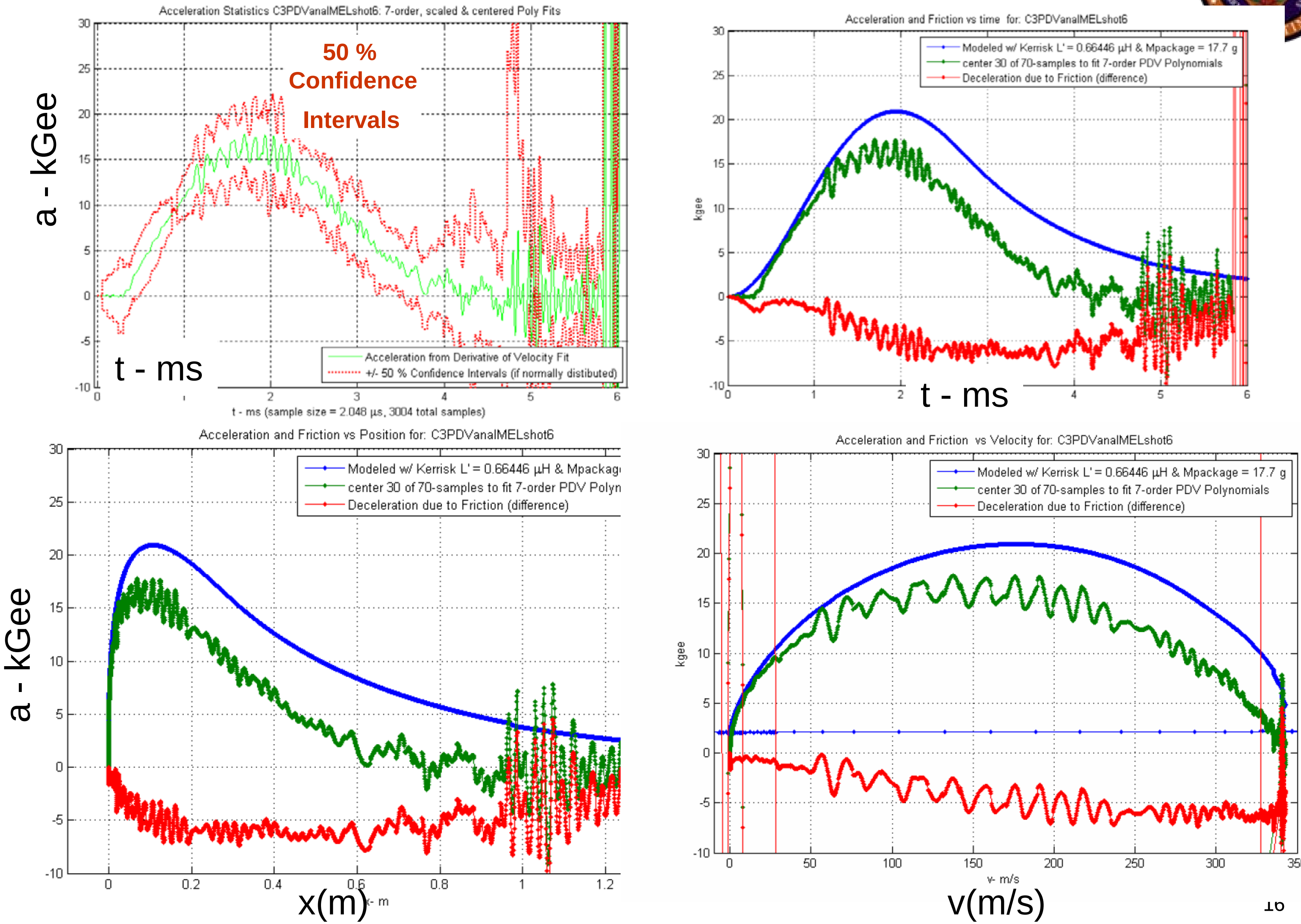


PDV Acceleration Statistics



t - ms

PDV Acceleration &Friction



So far . . .

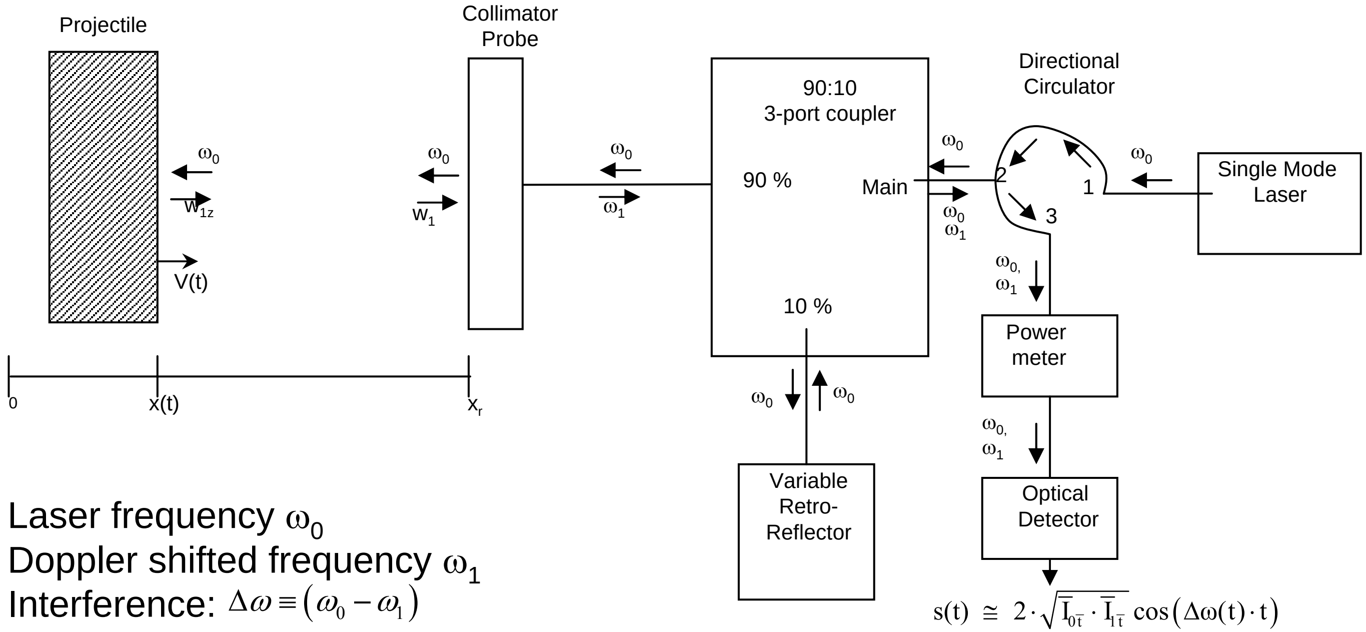
- Accurate velocity measurement is possible by measuring Doppler shift.
- Motion measurement is possible in the start-up region where use of B-dot probes is problematic.
- This method will help assess effects of lubrication on start-up armature behavior.
- The data shows interesting dynamic friction behavior at sliding contact.
- Future work: direct measurement of acceleration

[1] "High resolution sliding velocity measurement for assessing dynamic friction effects," Sikhanda Satapathy, Scott Levinson, Dwight Landen, David Holtkamp, and Adam Iverson, ASME Applied Mechanics and Materials Conference
June 3-7, 2007, University of Texas at Austin

Next Let's Consider:

- Direct measurement of acceleration Incorporating VISAR principals
- Quick Look at Long range (18 m) and poor reflecting surfaces
- Feasibility of using Multiple probes for balloting measurement

" Standard" PDV Directly Yields Velocity



Laser frequency ω_0

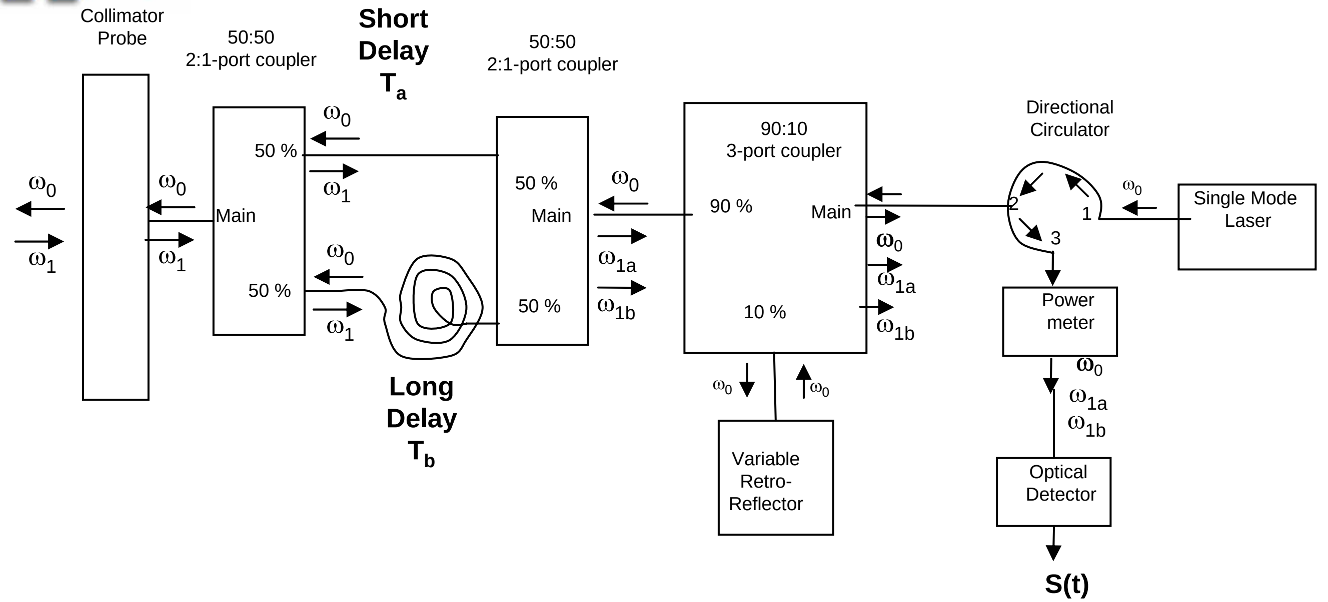
Doppler shifted frequency ω_1

Interference: $\Delta\omega \equiv (\omega_0 - \omega_1)$

Detected signal: $s(t) \cong 2\cdot\sqrt{\overline{I}_{0\bar{t}}\cdot\overline{I}_{1\bar{t}}}\cos\left(\Delta\omega(t)\cdot t\right) = 3.8\mathrm{V/mW}\cdot\sqrt{\overline{I}_{0\bar{t}}\cdot\overline{I}_{1\bar{t}}}\cos\left\{2\omega_0\dfrac{v_{\bar{t}} + a_{\bar{t}}\cdot t}{c}t\right\}.$

Terms incorporated in a subscript $\bar{t}$ indicate that they are calculated or measured by averaging over a small time interval τ centered about $\bar{t}$. Note that the amplitude of the detected signal $|s(t)|$ is proportional to the square-root of the received signal amplitude ($\sqrt{\overline{I}_{1\bar{t}}}$), and is adjustable by simply varying laser source amplitude ($\sqrt{\overline{I}_{0\bar{t}}}$).

Use "VISAR-Like" PDV for Acceleration



$$S(t) \cong 3.8\,\mathrm{V/mW}\left(\begin{array}{l}\sqrt{\bar{I}_{0\bar{t}}\cdot \bar{I}_{1a\bar{t}}}\,\cos\left(\left(\omega_0-\omega_{1a}\right)\cdot t\right)+\sqrt{\bar{I}_{0\bar{t}}\cdot \bar{I}_{1b\bar{t}}}\,\cos\left(\left(\omega_0-\omega_{1b}\right)\cdot t\right)\\ +\sqrt{\bar{I}_{1a\bar{t}}\cdot \bar{I}_{1b\bar{t}}}\,\cos\left(\left(\omega_{1a}-\omega_{1b}\right)\cdot t\right)\end{array}\right)$$

Noting: $\omega_1(t)=\omega_0\left(1+\dfrac{2v(t)}{c}\right)$, we observe that

$$\omega_{1a}=\omega_0\left(1+2\frac{\bar{v}_{\bar{t}}+\bar{a}_{\bar{t}}\cdot\left(T_a-\bar{t}\right)}{c}\right)$$

$$\omega_{1b}=\omega_0\left(1+2\frac{\bar{v}_{\bar{t}}+\bar{a}_{\bar{t}}\cdot\left(T_b-\bar{t}\right)}{c}\right)$$

"VISAR-Like" PDV for Acceleration cont.

Three signal components offer an independent means to detect the velocity in the vicinity of time T_a and T_b, and with average acceleration between them. They have respective frequencies & amplitudes:

1) $|\omega_{1a} - \omega_0| = 2\omega_0 \dfrac{\bar{v}_{\bar{t}} + \bar{a}_{\bar{t}} \cdot (T_a - \bar{t})}{c}$ at amplitude $\sqrt{\bar{I}_{0\bar{t}} \cdot I_{1a\bar{t}}}$

2) $|\omega_{1b} - \omega_0| = 2\omega_0 \dfrac{\bar{v}_{\bar{t}} + \bar{a}_{\bar{t}} \cdot (T_b - \bar{t})}{c}$ at amplitude $\sqrt{\bar{I}_{0\bar{t}} \cdot I_{1b\bar{t}}}$

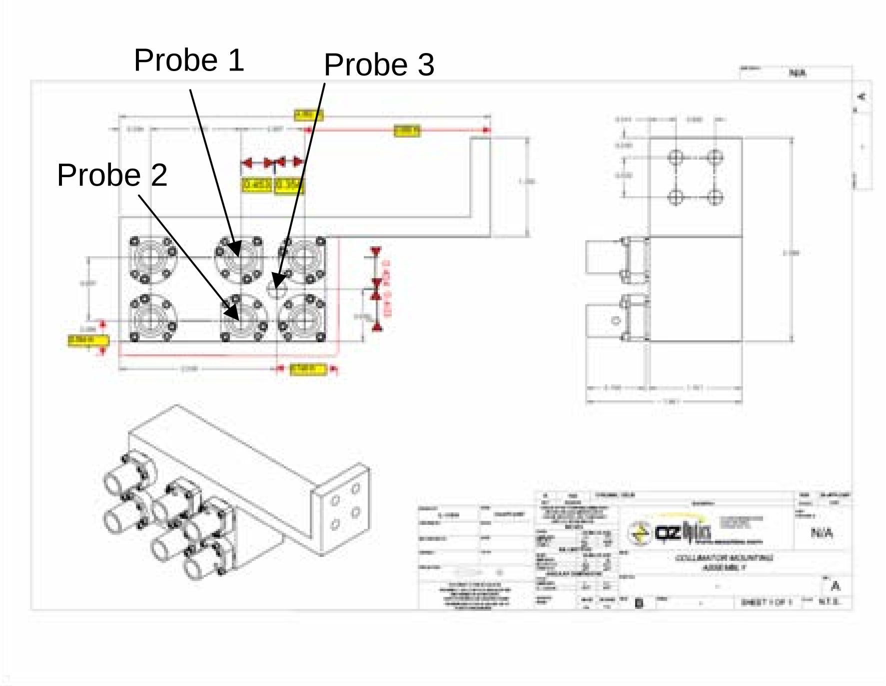
3) $|\omega_{1b} - \omega_{1a}| = 2\omega_0 \dfrac{\bar{a}_{\bar{t}} \cdot (T_b - T_a)}{c}$ at amplitude $\sqrt{I_{1a\bar{t}} \cdot I_{1b\bar{t}}}$

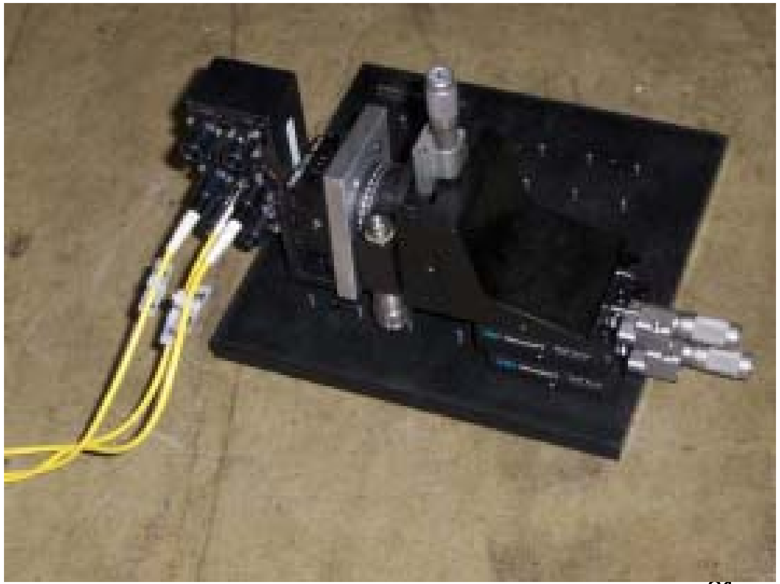
The 3rd component's frequency is **proportional to acceleration** $\Rightarrow$ directly measurable!

However, it's amplitude, $\sqrt{I_{1a\bar{t}} \cdot I_{1b\bar{t}}}$, is typically 10-20 dB smaller than the other 2 components $\Rightarrow$ may result in poor S/N.

Quick Look at PDV w/ 3 probes over LONG (18-m) Range
- Reflecting Surface
- Balloting

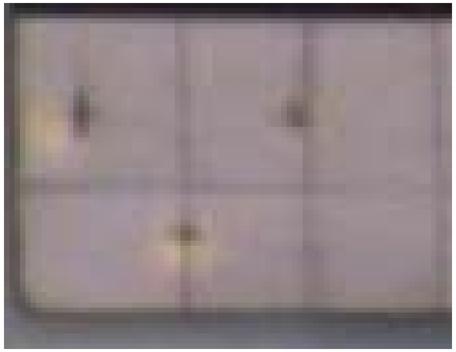
- Arrange 3 *Oz Optics* Probes in array
- At 18 m downrange from probes, wave reflector surfaces (by hand) :
  - Reflexite P66
  - unpolished al 7075
  - no surface
- Observe Spectrograms $\left|s\left(v_k,t\right)\right|$



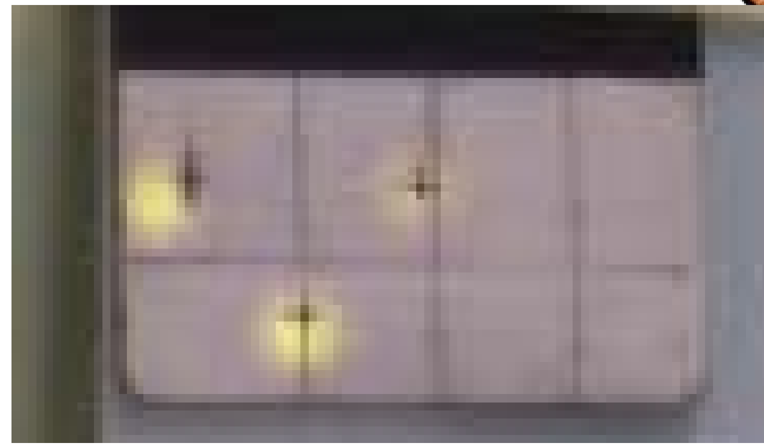


1-way Source to IR card Range: 18.0 m

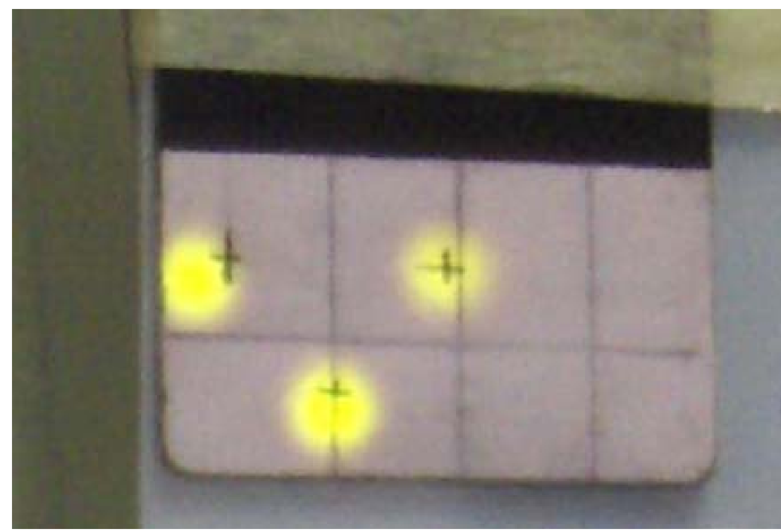
75 mW - each channel



150 mW - each channel

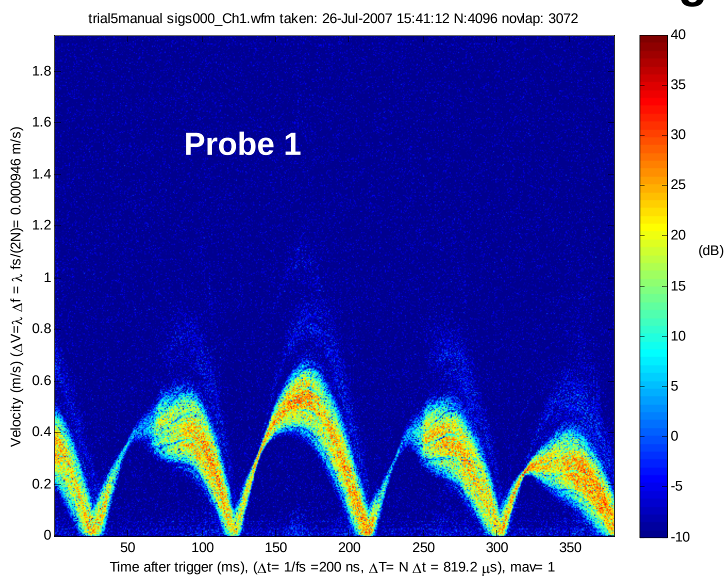


300 mW - each channel

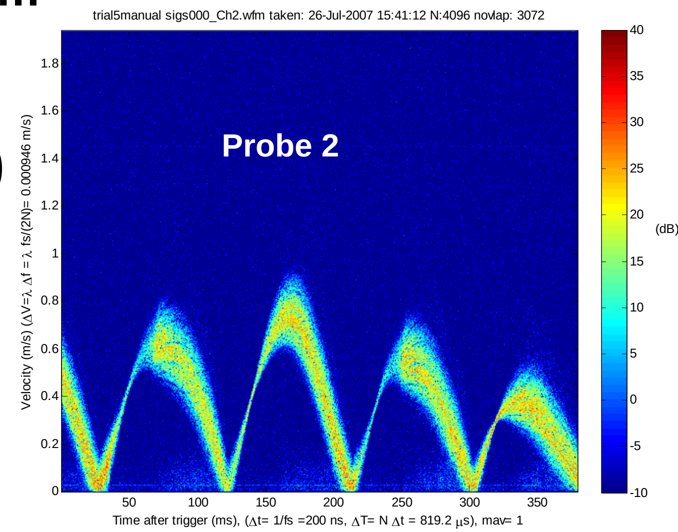


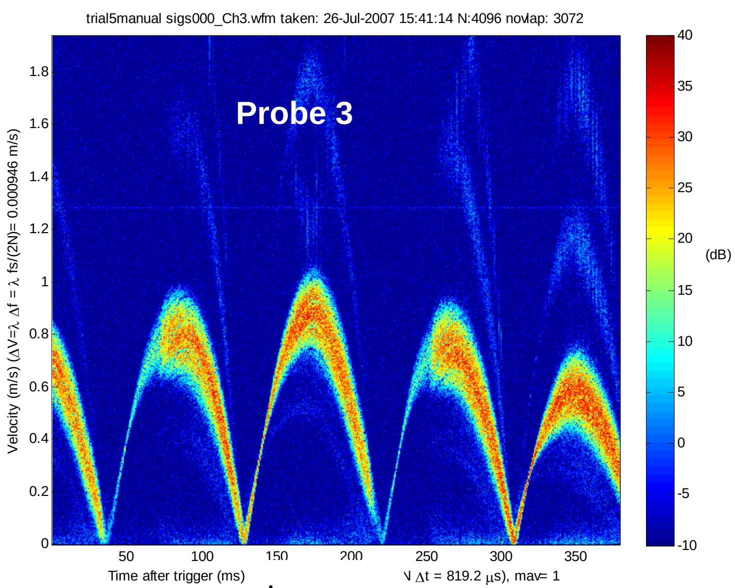
0.85 in

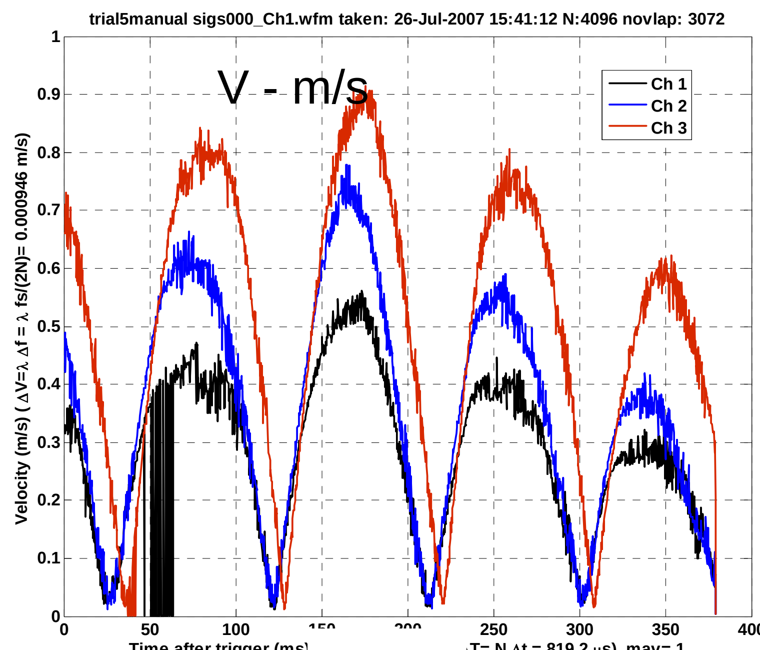
Trial 5: Moving RetroReflective Surface
300 mW - each channel, Adjustable Retro: - 2 dB each ch
Probe - Reflector Range: 18.0 m



S(v,t)



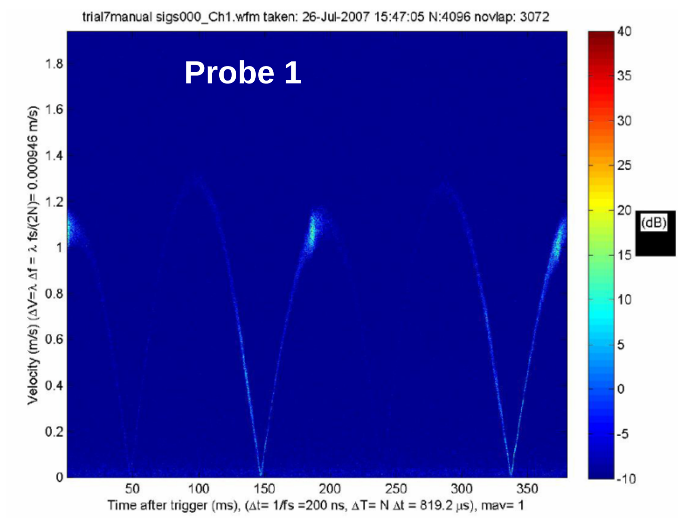




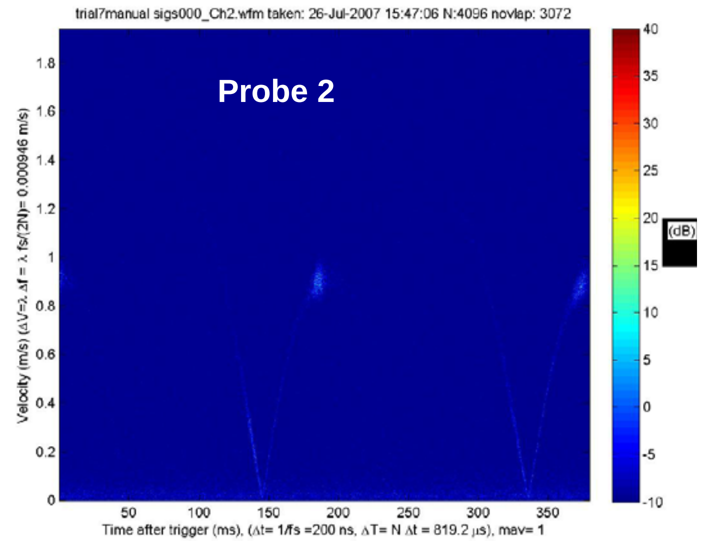
t - ms

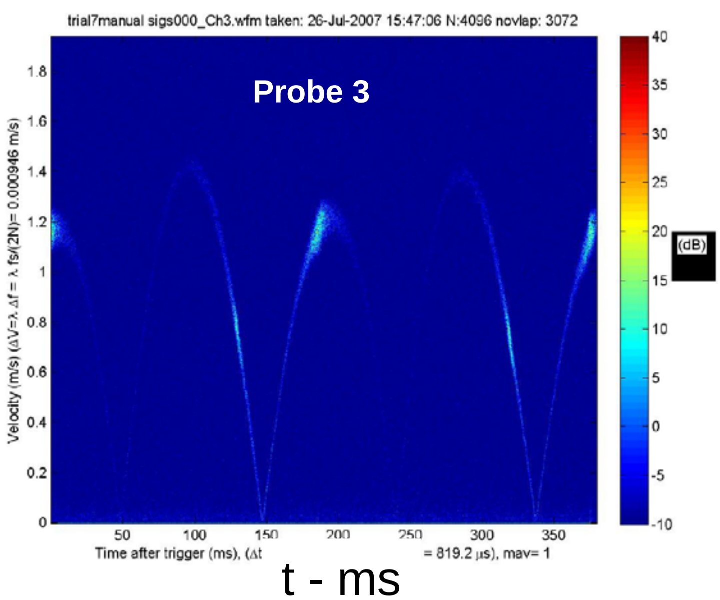
t - ms

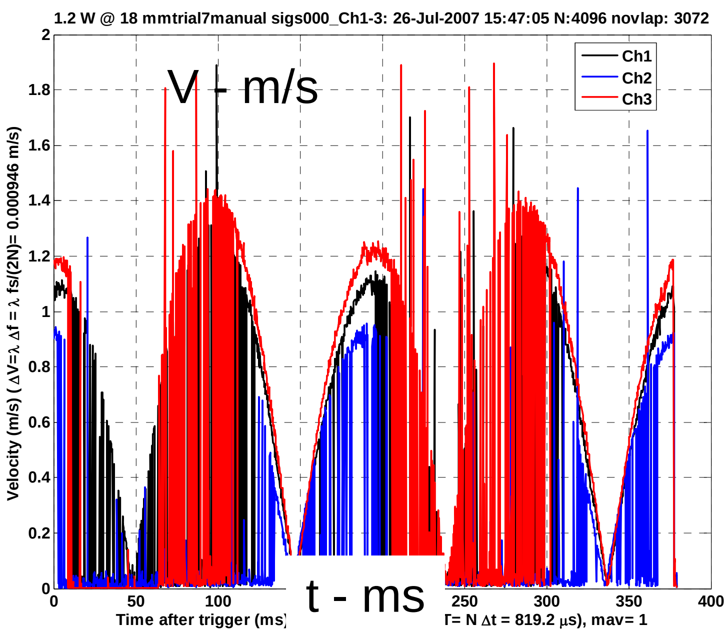
Trial 7: Moving Unpolished 7075 Surface
300 mW - each channel, Adjustable Retro: - 2 dB each ch
Probe - Reflector Range: 18.0 m



S(v,t)



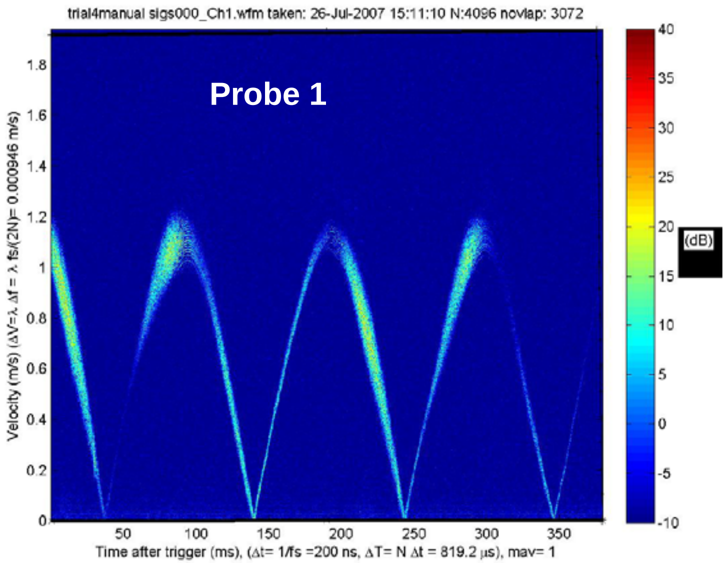




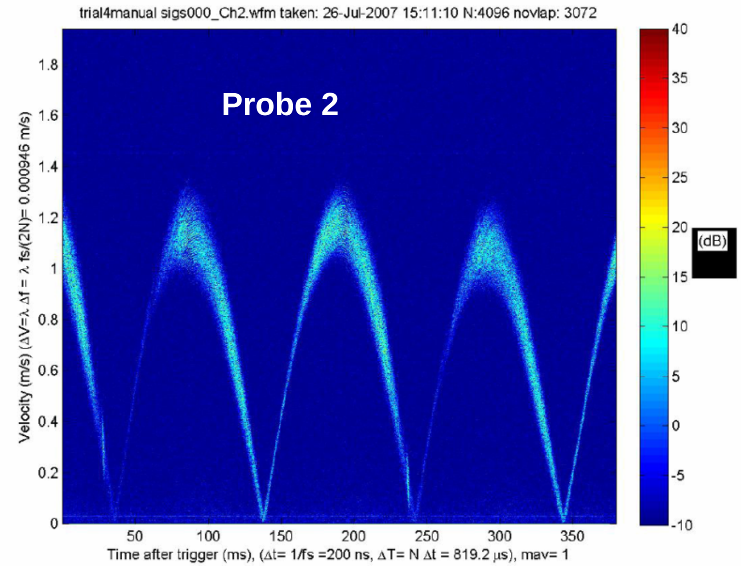
Trial 4: Moving RetroReflective Surface

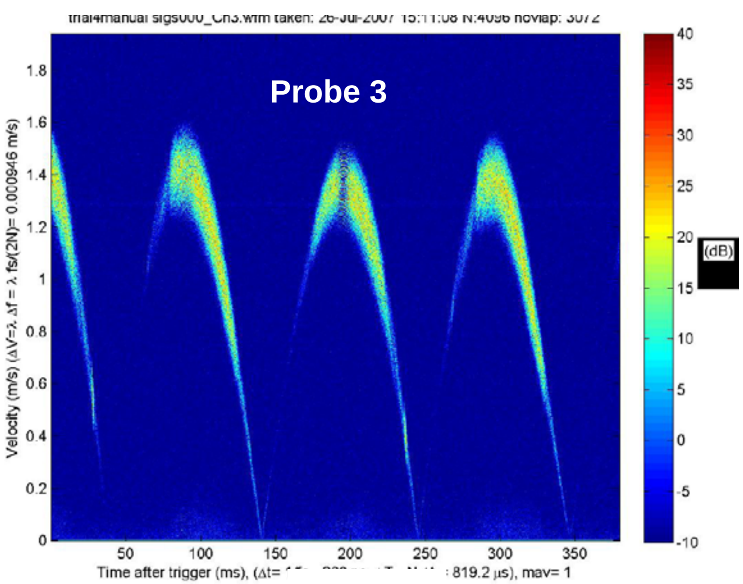
75 mW - each channel, Adjustable Retro: - 6dB each ch

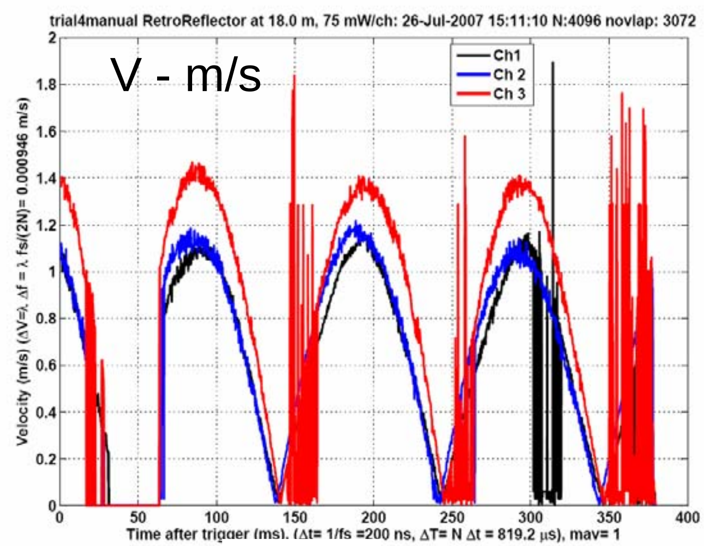
Probe - Reflector Range: 18.0 m



S(v,t)



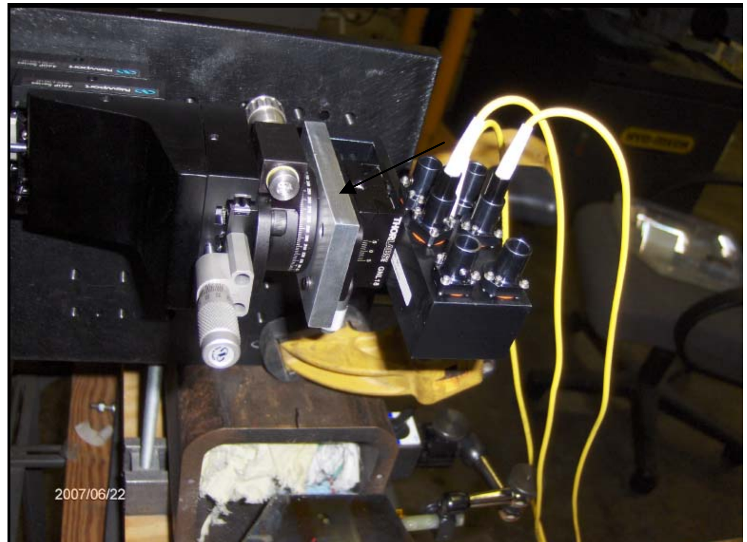




t - ms

t - ms

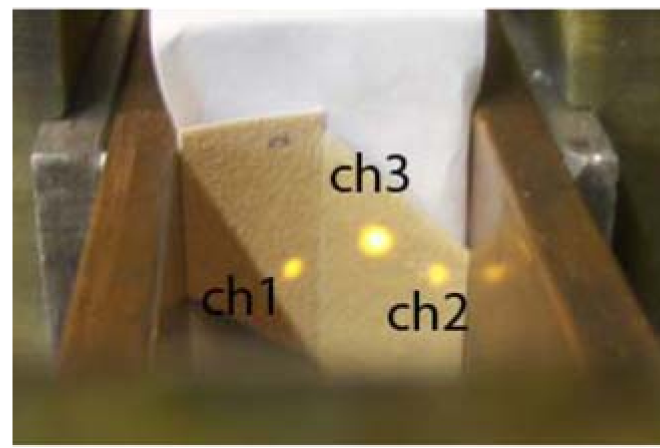
Use Multiple (Muzzle) Probes



Muzzle Probe Array (Oz Optics)

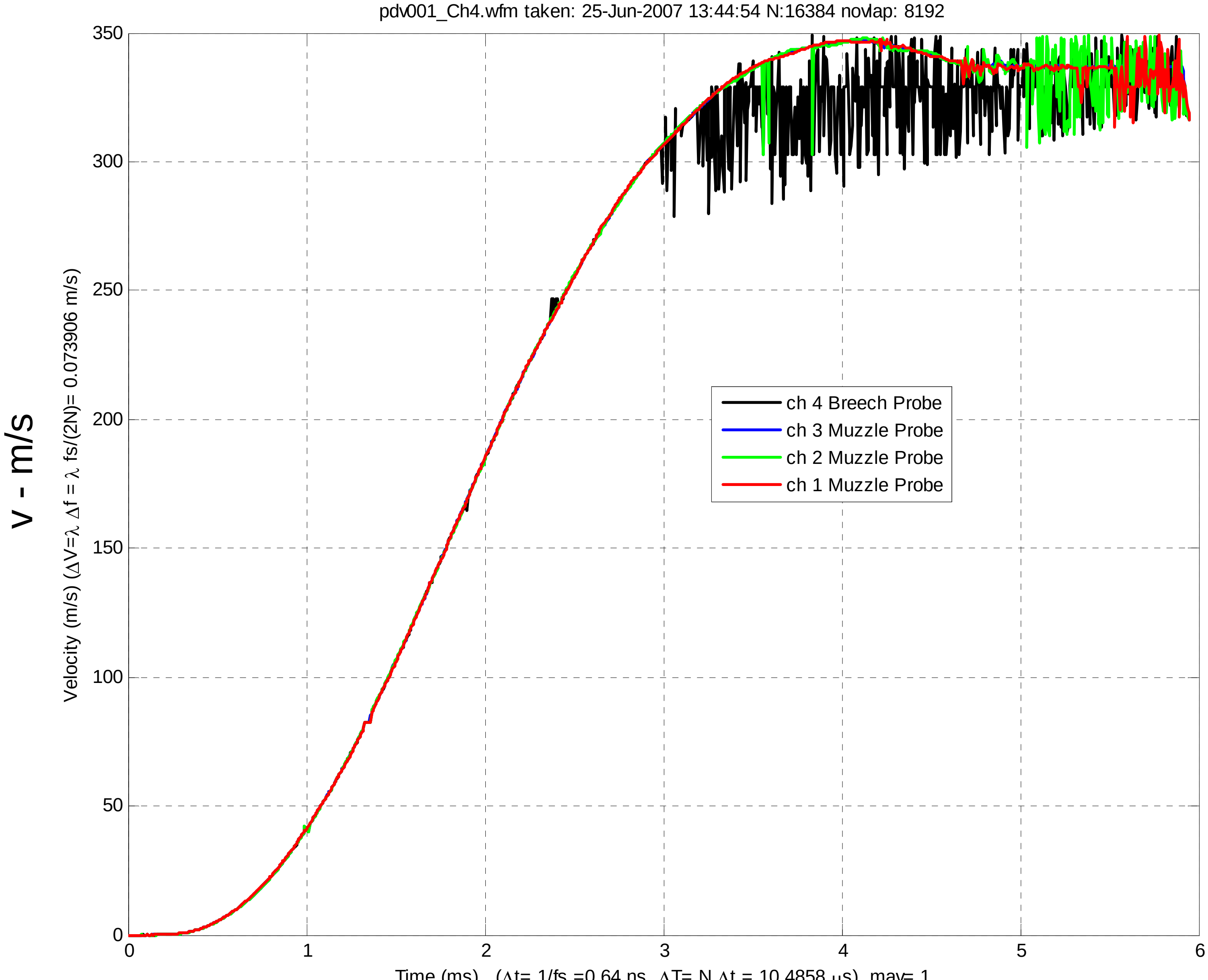
Muzzle Mirror

Downrange into Muzzle Mirror (1-mW 650 nm signal from FIS "Fault Detector" split into 3 probes)



Up-range into IR card at breech (IR Laser signal from each probe)

Breech and Muzzle Velocities with new Laser (with appropriate bracketing)



(2^{nd}) Summary

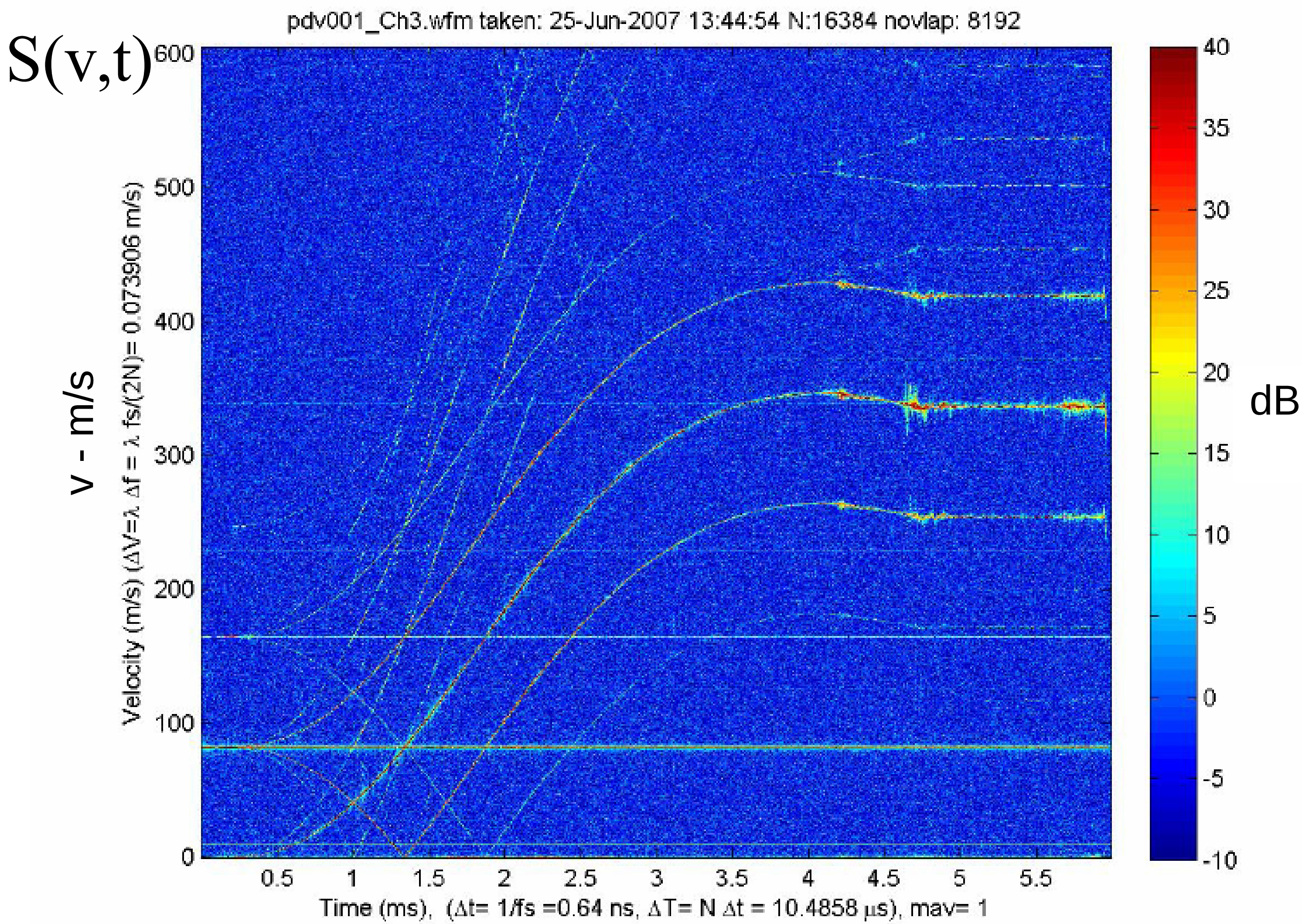
- Like VISAR, use of time delayed signals may allow direct PDV measurement of the acceleration
- A Quick-look shows PDV is likely to work over
  - long ranges,
  - with multiple, independent, closely-spaced signals,
  - & (maybe) w/ untreated launch-package surfaces.
- Multiple-independent signal detection in small railgun is feasible
- Future work:
  - Routinely characterize axial velocity profiles in large EM guns (e.g., HeMCL)
  - Test direct measurements of axial acceleration & 3d balloting

[1] "Photonic Doppler Velocimetry in the Bore of a Railgun", http://www.emlsymposium.org/about.html,
[2] "High resolution acceleration measurements," http://www.emlsymposium.org/about.html

[3] "Balloting Motion Measurement in Railgun," http://www.emlsymposium.org/about.html

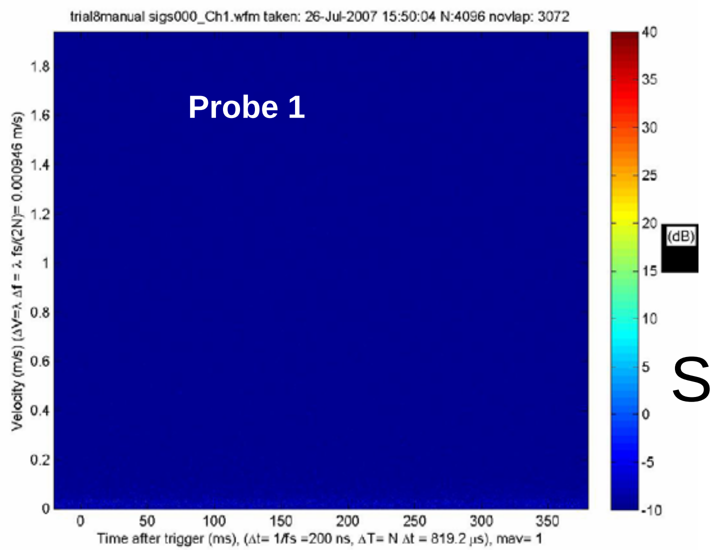
Extras

Spectrogram of New Laser

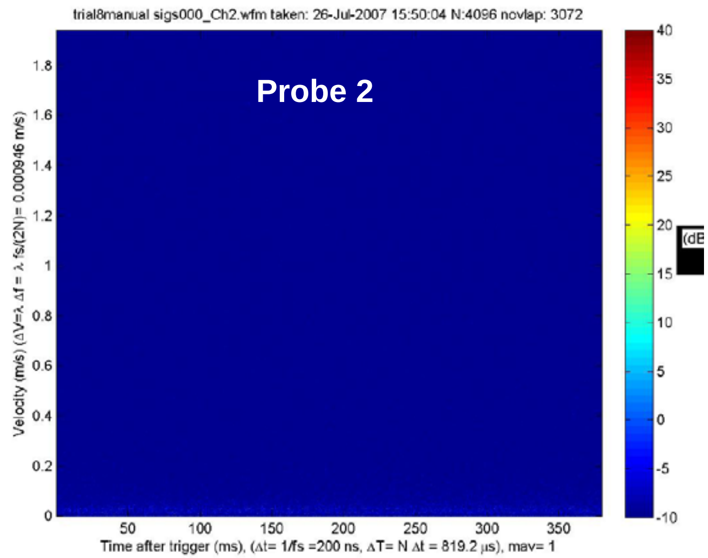


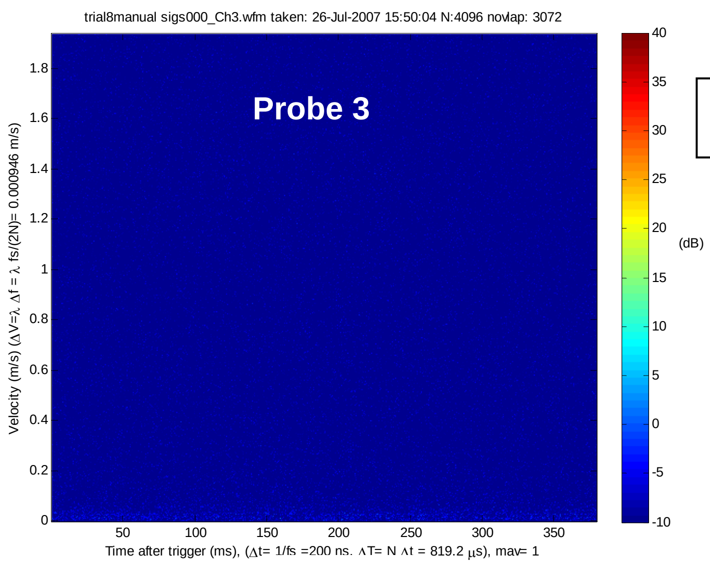
Multiple Velocities result from aliasing & multiple lines (1.667 GHz)
(from new IPG Laser, which is now fixed)

Trial 8: No Moving Surface
300 mW - each channel, Adjustable Retro: - 2 dB each ch
Probe - Reflector Range: 18.0 m

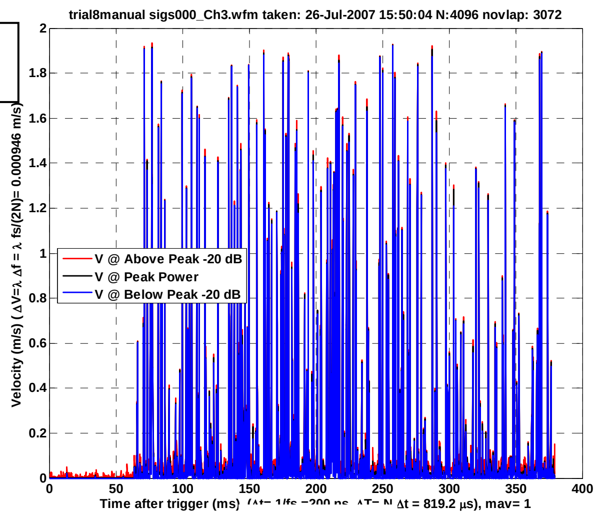


S(v,t)





V - m/s



t - ms

t - ms

Trial 8: No Moving Surface
300 mW - each channel, Adjustable Retro: - 2 dB each ch
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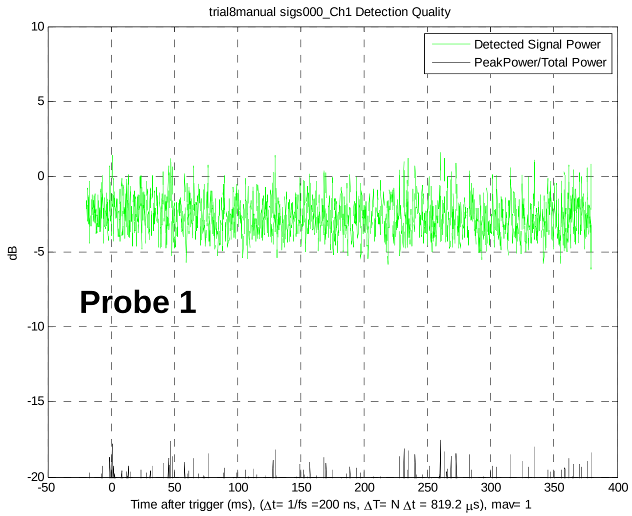
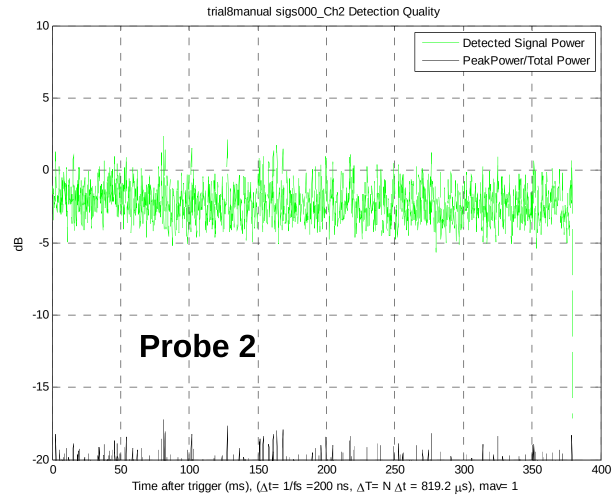
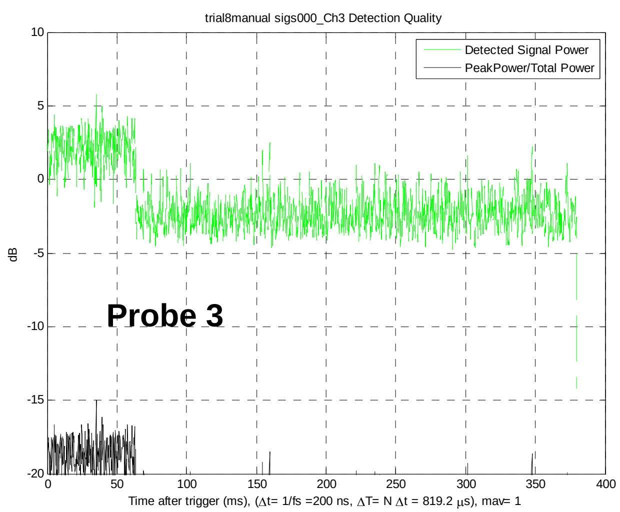


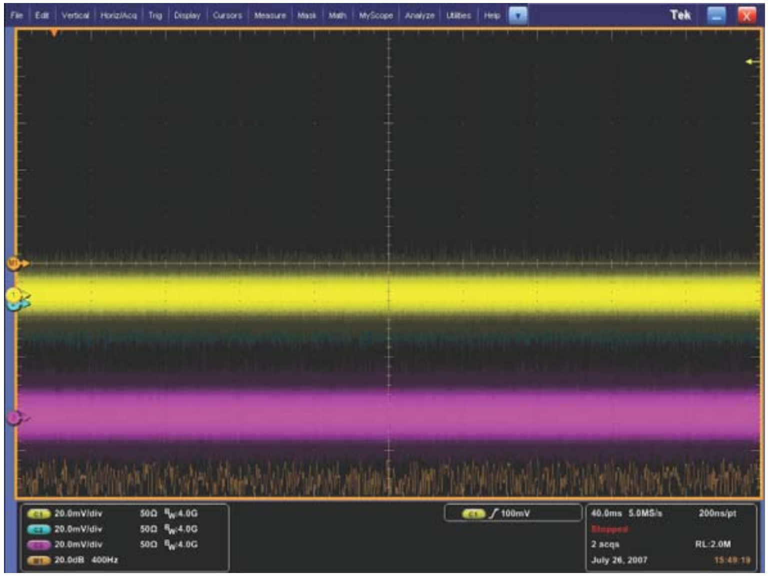
S

S/N





Tektronix Scope ⇒ Traces



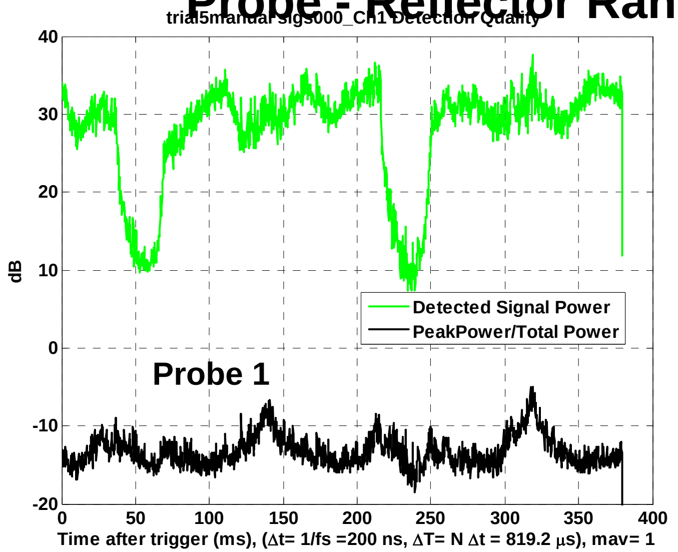
t - ms

t - ms

Trial 5: Moving RetroReflective Surface

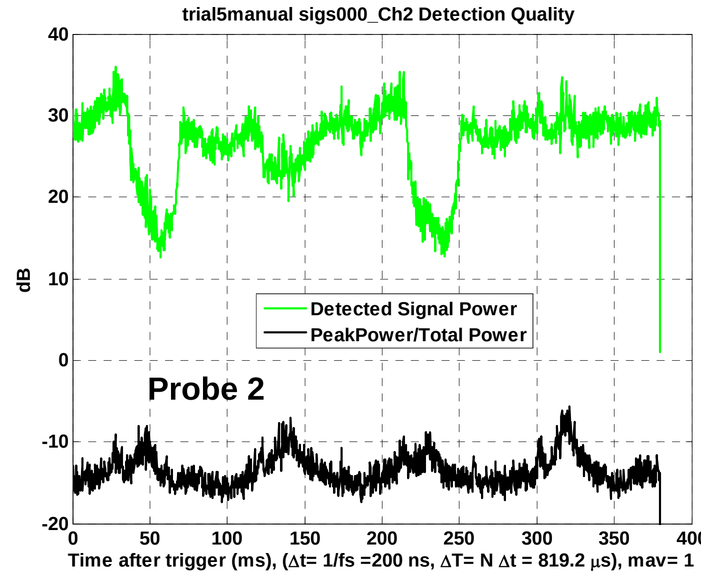
300 mW - each channel, Adjustable Retro: - 2 dB each ch

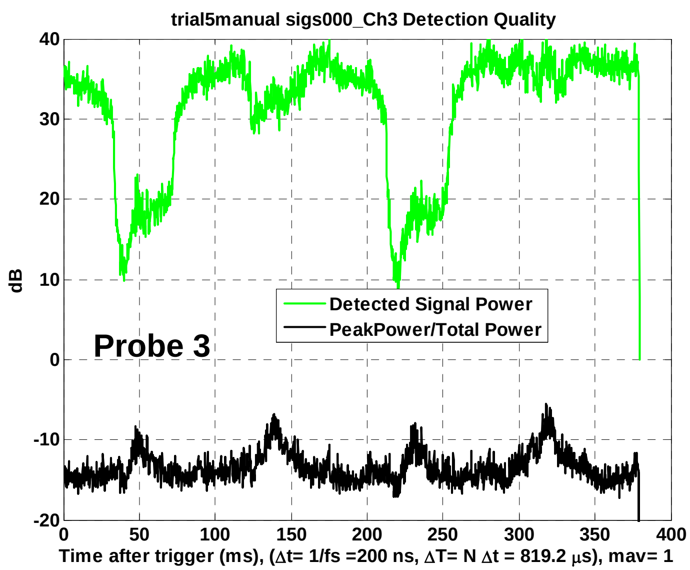
Probe - Reflector Range: 18.0 m



S

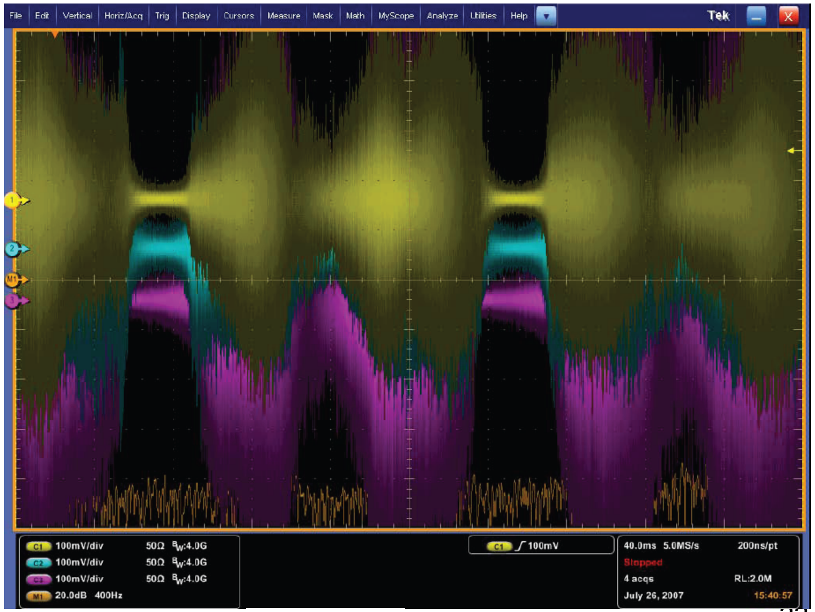
S/N





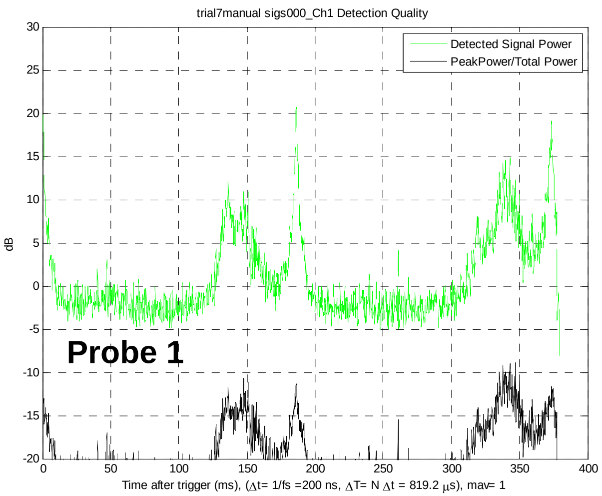
t - ms

Tektronix
Scope ⇒
Traces



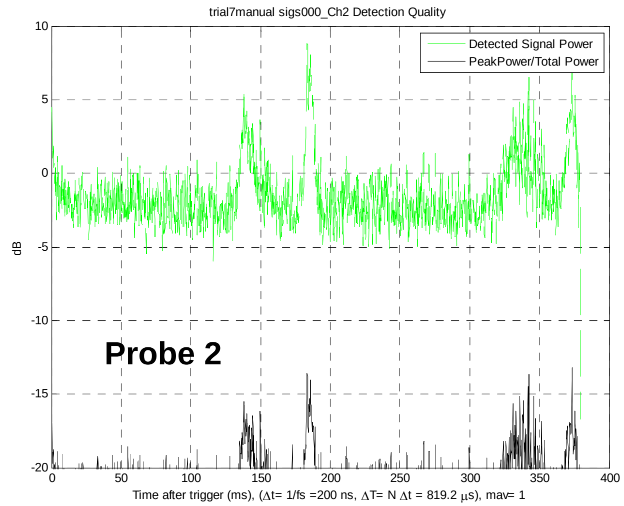
t - ms

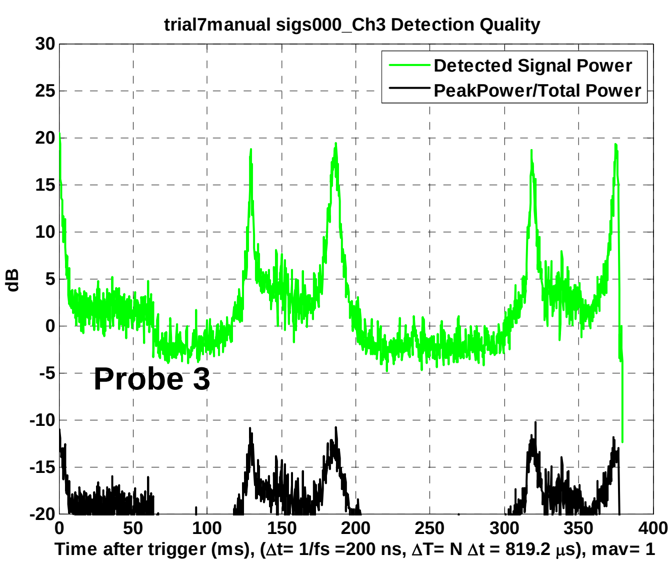
Trial 7: Moving Unpolished 7075 Surface
300 mW - each channel, Adjustable Retro: - 2 dB each ch
Probe - Reflector Range: 18.0 m



S

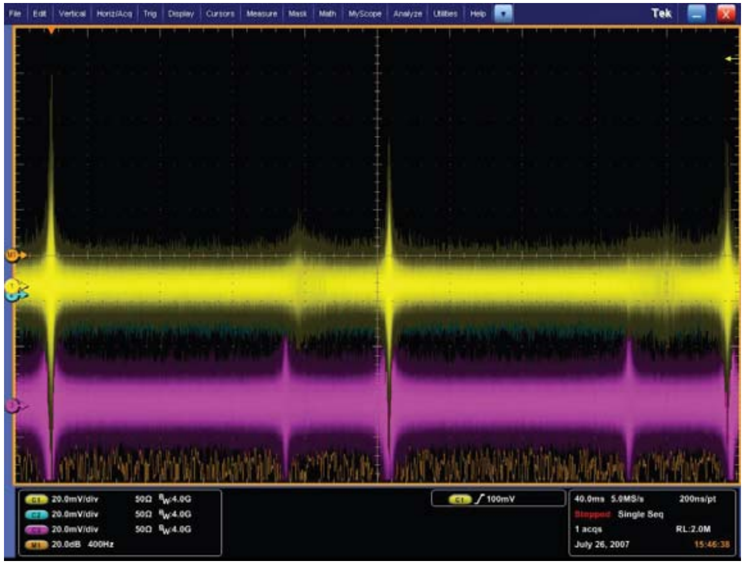
S/N





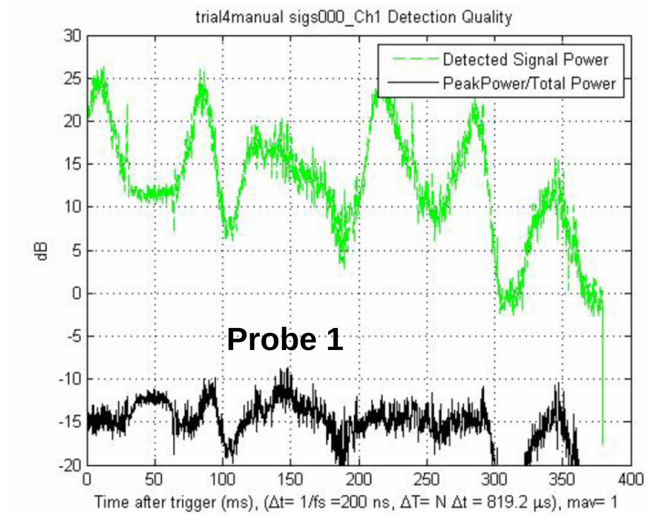
t - ms

Tektronix Scope ⇒ Traces



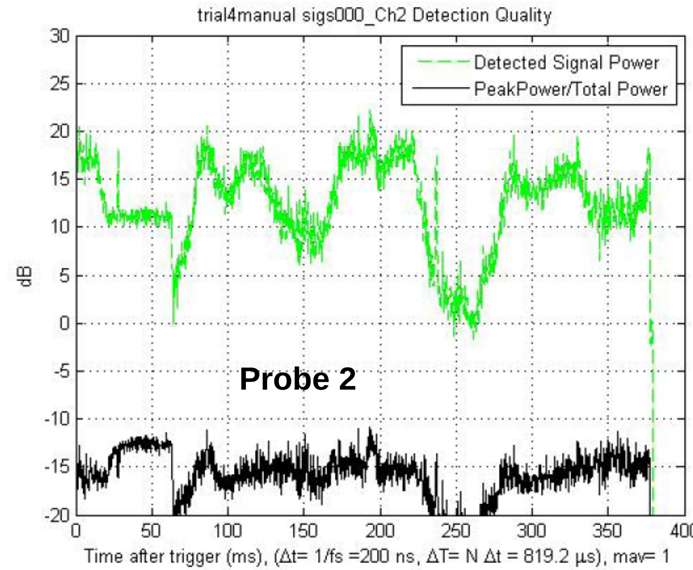
t - ms

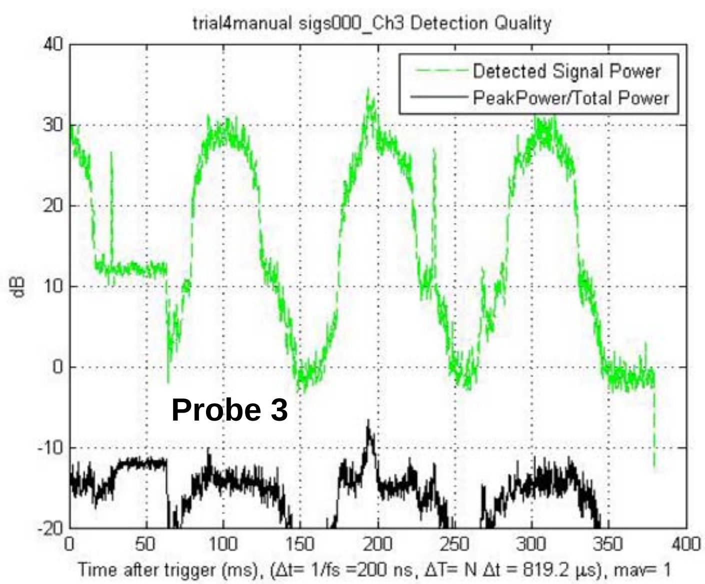
Trial 4: Moving RetroReflective Surface
75 mW - each channel, Adjustable Retro: - 6dB each ch
Probe - Reflector Range: 18.0 m



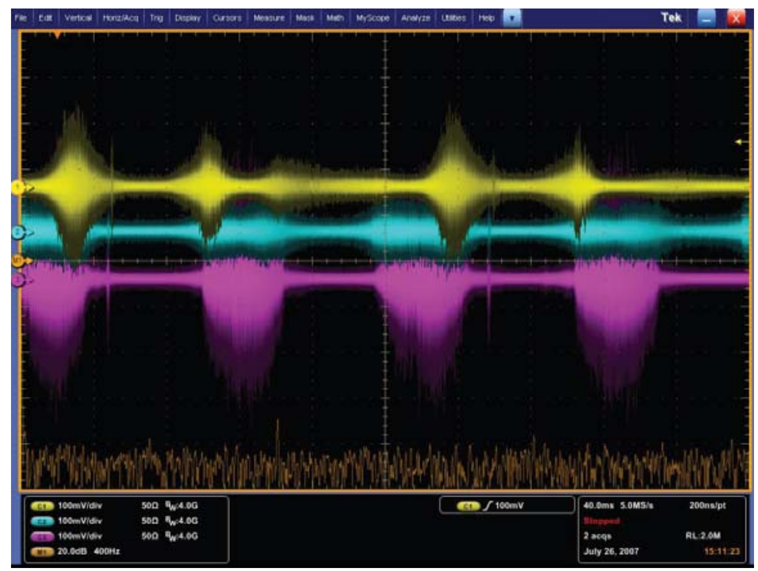
S

S/N





Tektronix Scope ⇒ Traces



t (ms)

t (ms)