DOE/NV/25946--004

Variations on PDV

~ or ~

How to Complicate an Elegantly Simple Measurement without Really Trying

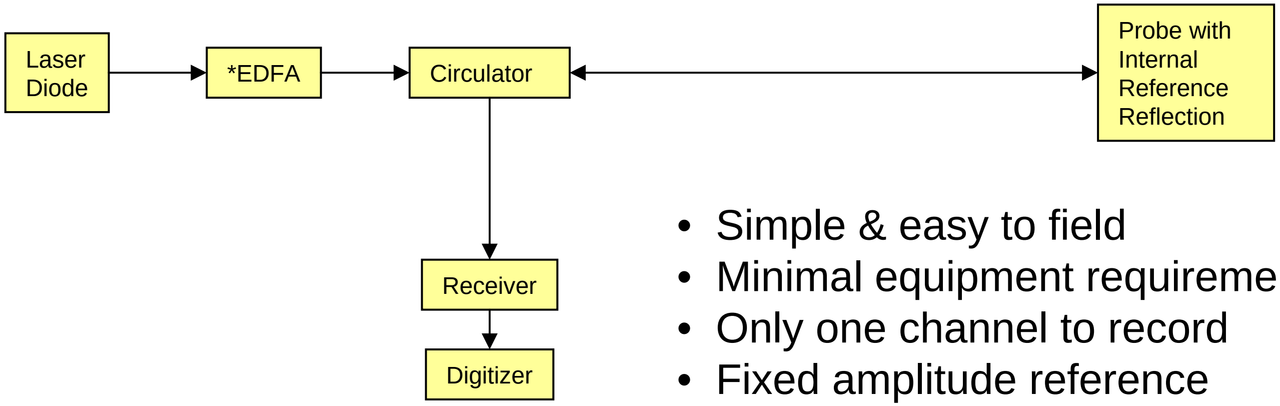
Bruce Marshall
Special Technologies Laboratory
July 20, 2006

This work was supported by the U.S. Department of Energy National Nuclear Security Administration Nevada Site Office under Contract Nos. DE-AC08-96NV11718 and DE-AC52-06NA25946

Areas of interest

- Conventional PDV
- Quadrature PDV
- Heterodyne / downconversion PDV systems
- Signal improvement & noise reduction
- Probes
- High power pulsed laser
- Velocity Interferometry

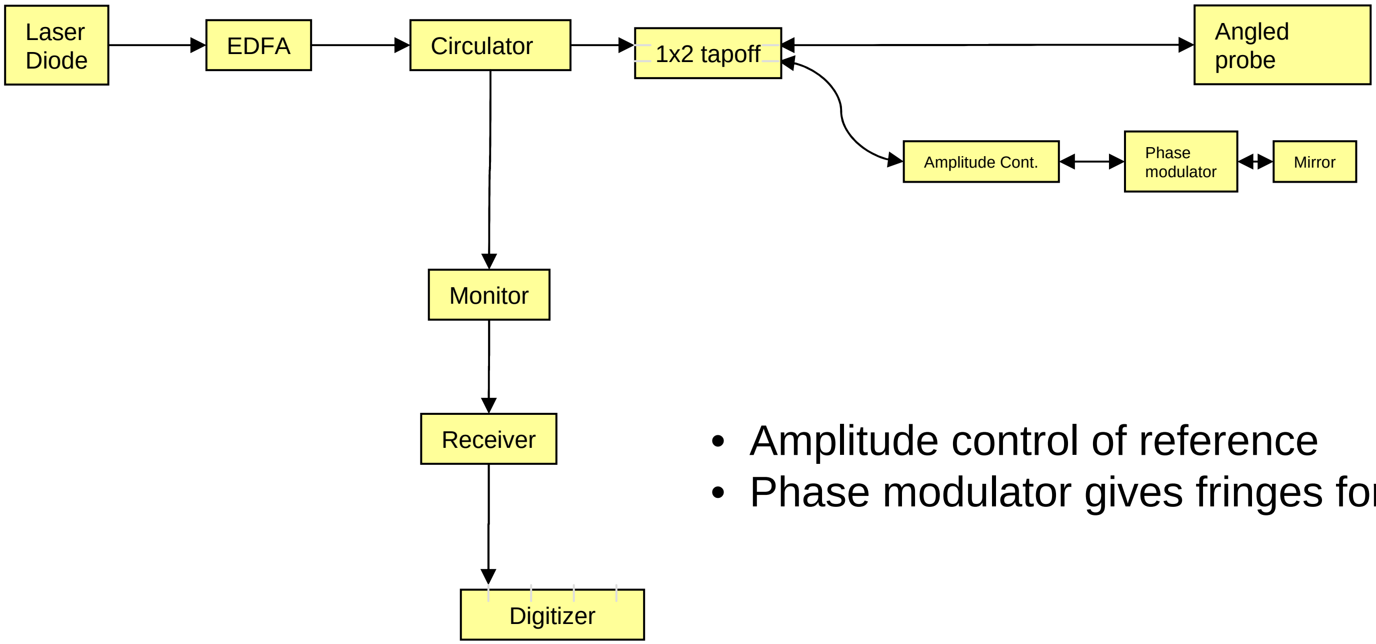
Basic PDV with internal reference



- Simple & easy to field
- Minimal equipment requirements
- Only one channel to record
- Fixed amplitude reference

* Erbium Doped Fiber Amplifier

Basic PDV with external reference

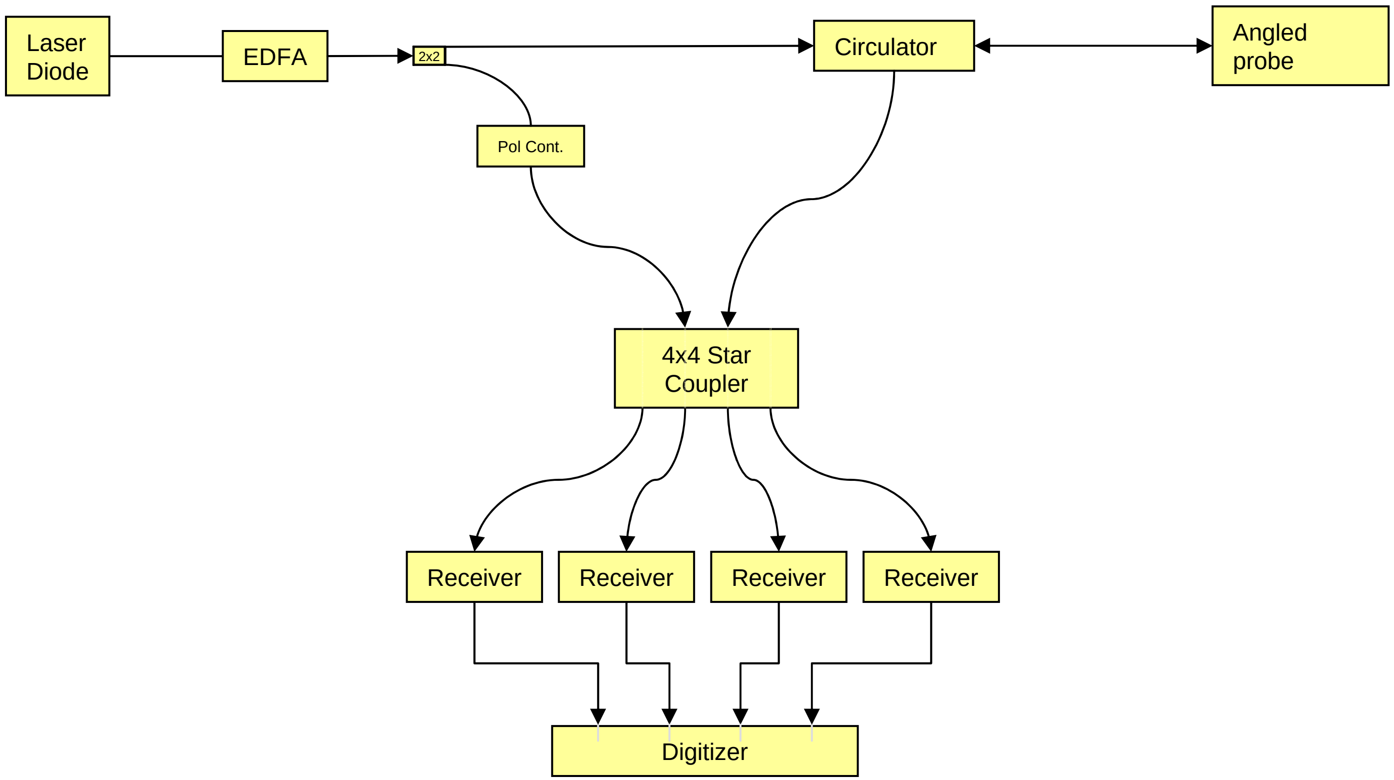


- Amplitude control of reference
- Phase modulator gives fringes for setup

Quadrature PDV

- Preserves directional information.
- Possible improvement in direct unfold of fringes, perhaps giving better time resolution than the sliding FFT.
- Can be realized with bulk optics or waveguide devices such as 3x3 or 4x4 splitters.
- Requires 2, 3, or 4 recording channels

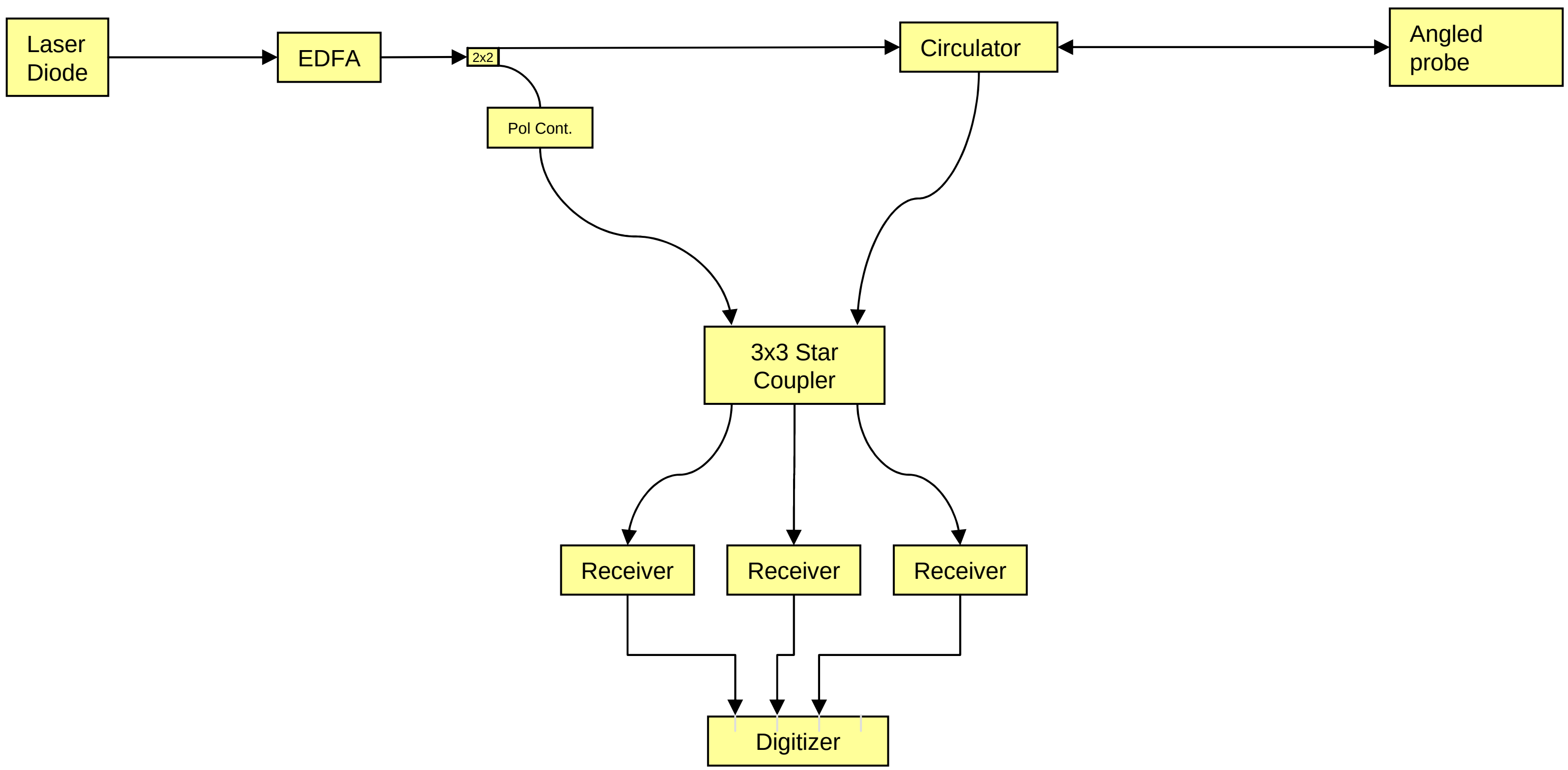
Basic Configuration for PDV with Quadrature & Complementary Outputs



- 4x4 with stable, accurate phase relationships may not be readily available.

3x3 PDV

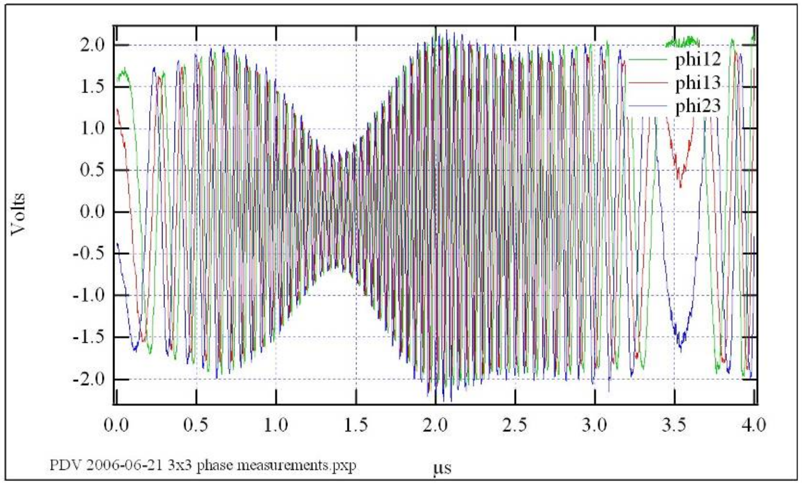
- Outputs are separated by 120° phase. Quadrature signals can be calculated from the 120° outputs.
- Reasonably accurate 3x3 couplers have been developed for the Fiber Optic Gyro industry.

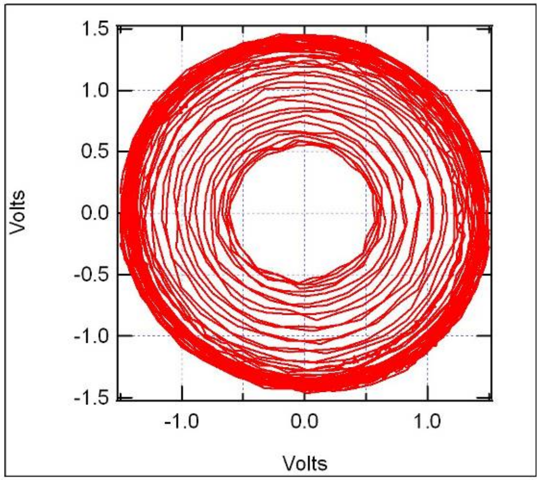


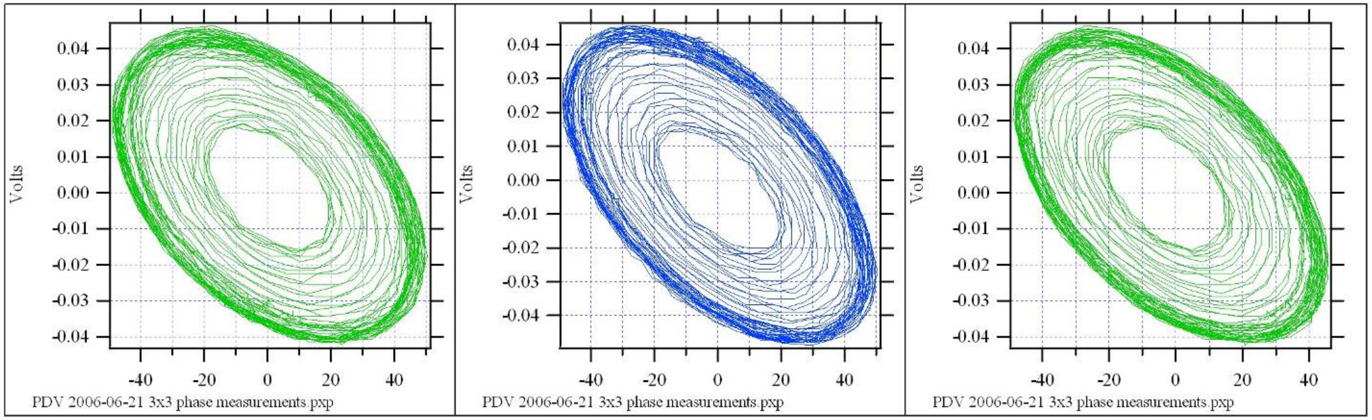
Quadrature Components from 3x3 Outputs

- Data from fiber interferometer with fiber stretcher in reference leg.

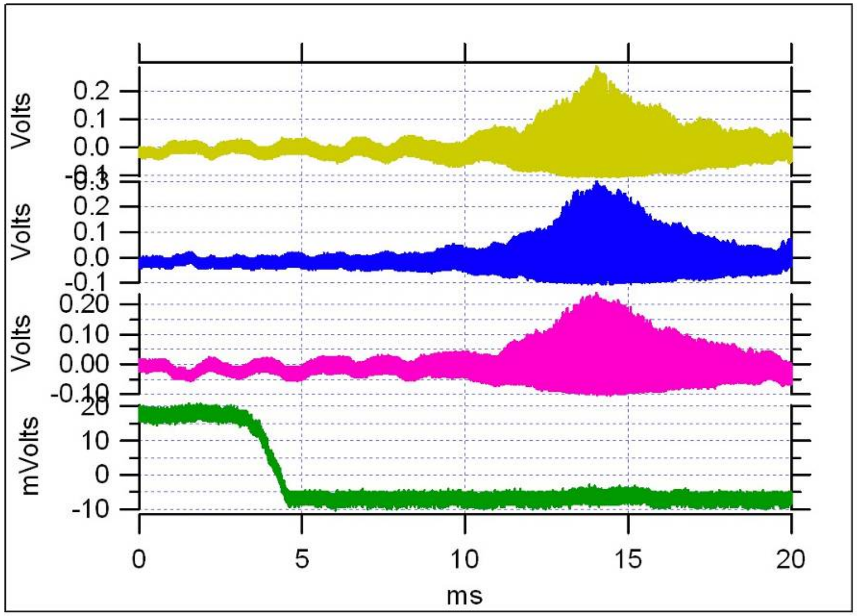
$$OPD = \frac{\lambda}{2\pi}\arctan\left(\sqrt{3}\,\frac{I_+ - I_-}{2I_s - I_+ - I_-}\right)$$

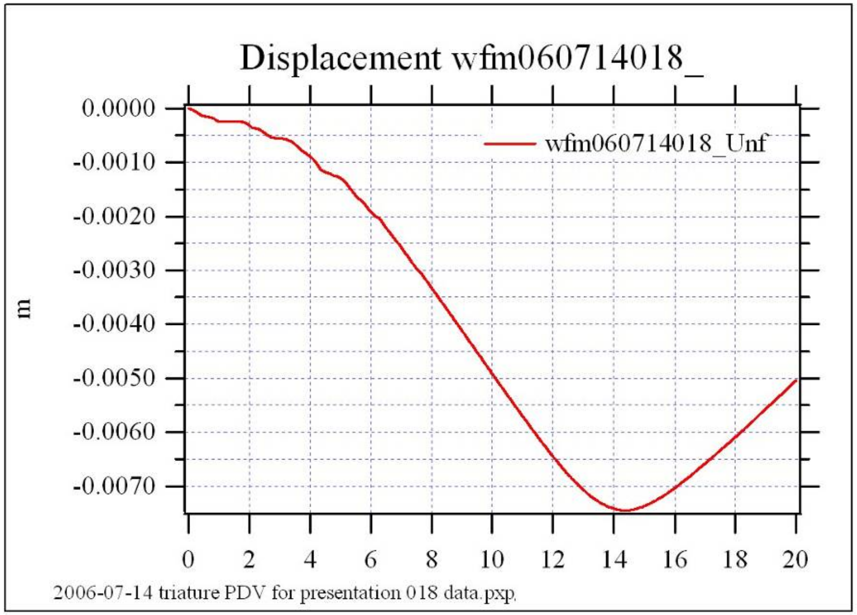


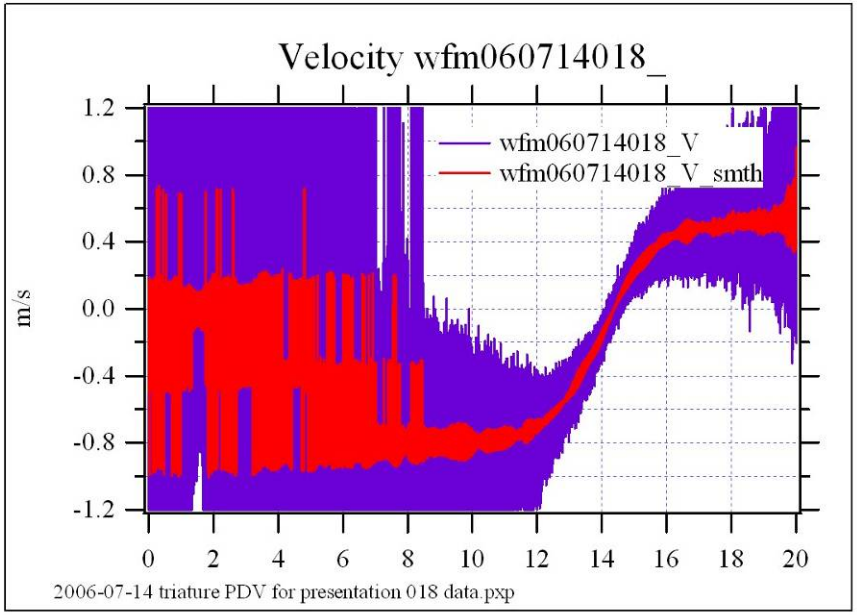


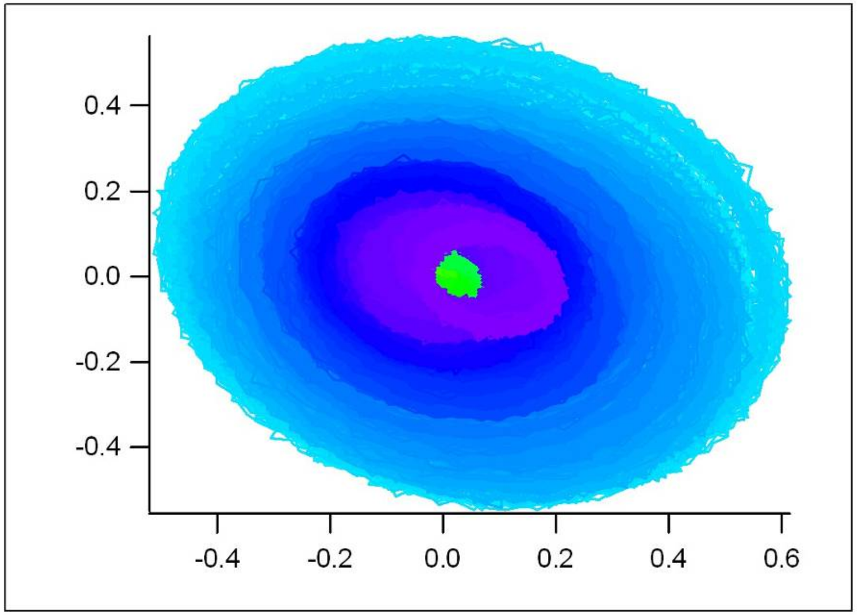


Quadrature PDV, Mirror target, single fiber probe

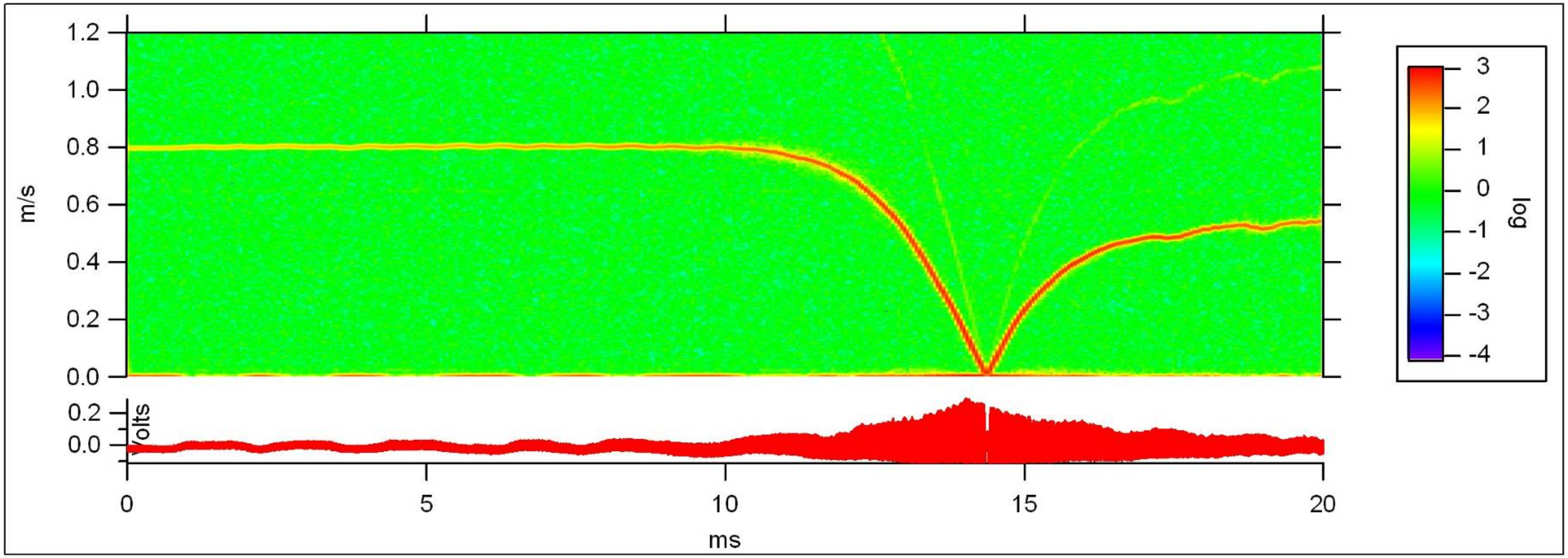


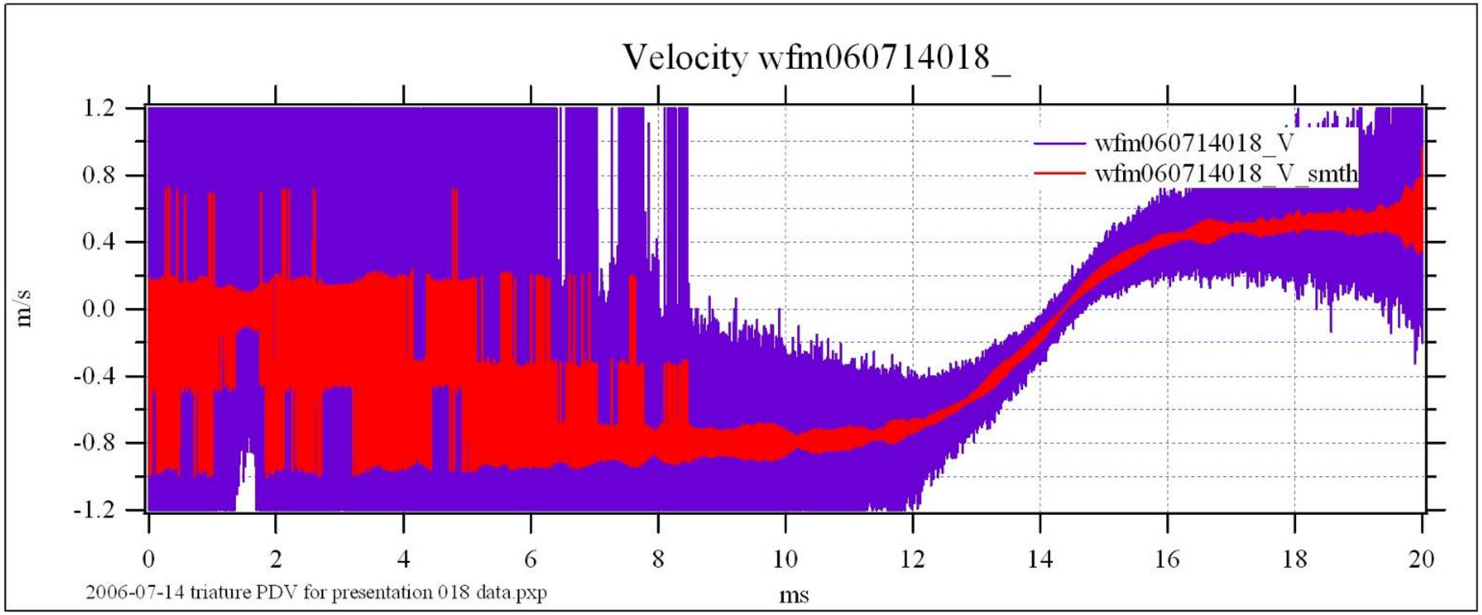




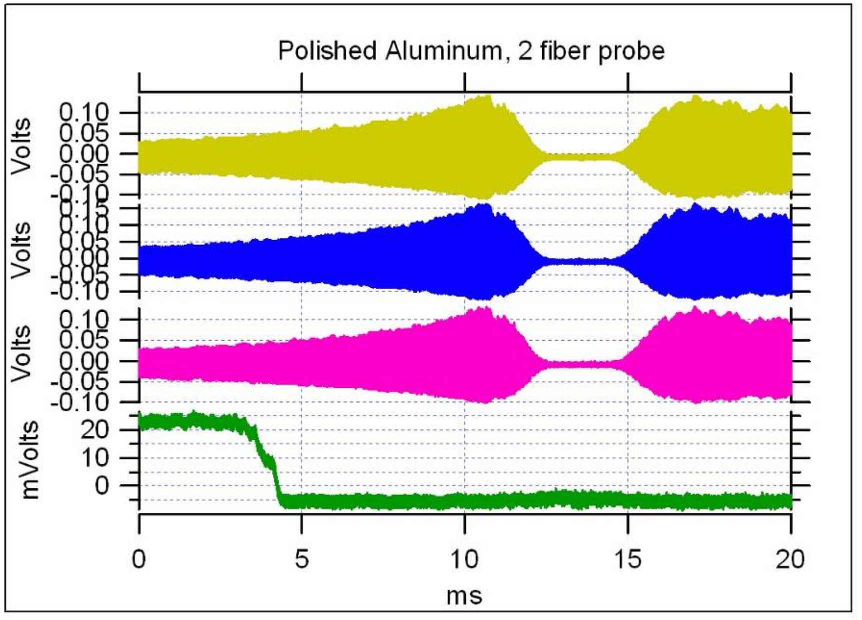


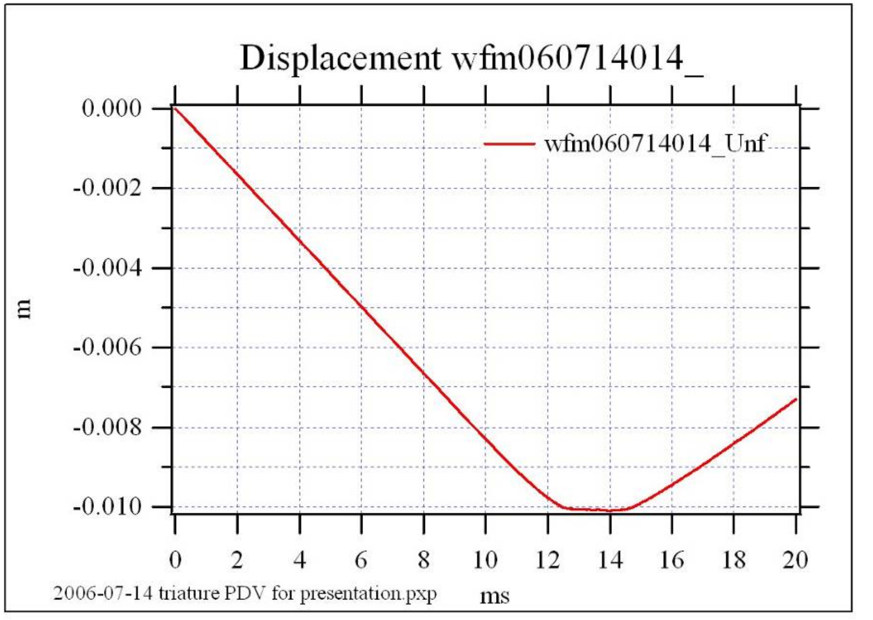
Quadrature PDV, Mirror target, single fiber probe

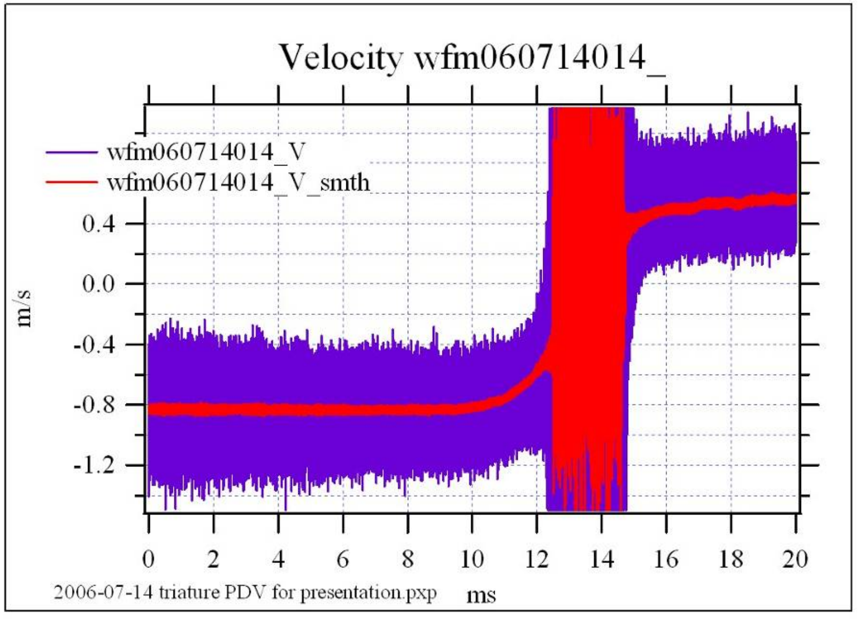


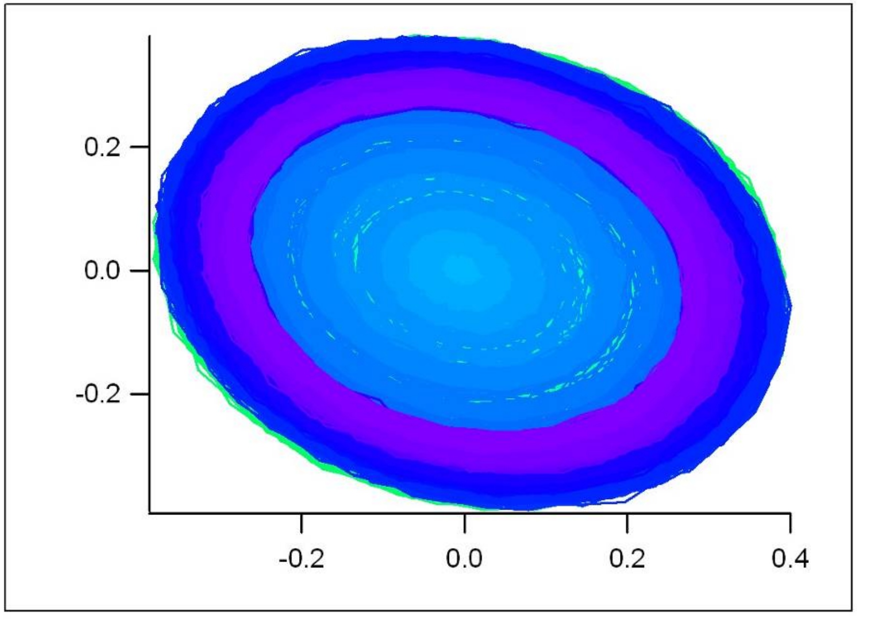


Quadrature PDV, Mirror target, two fiber probe

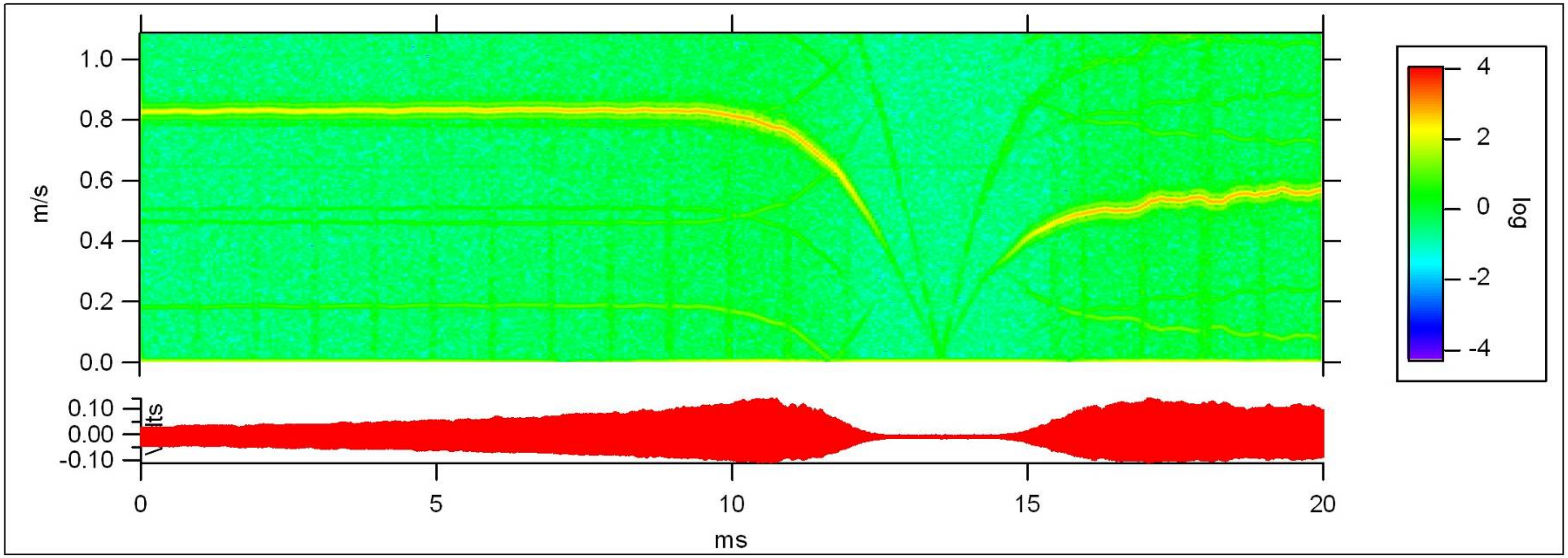


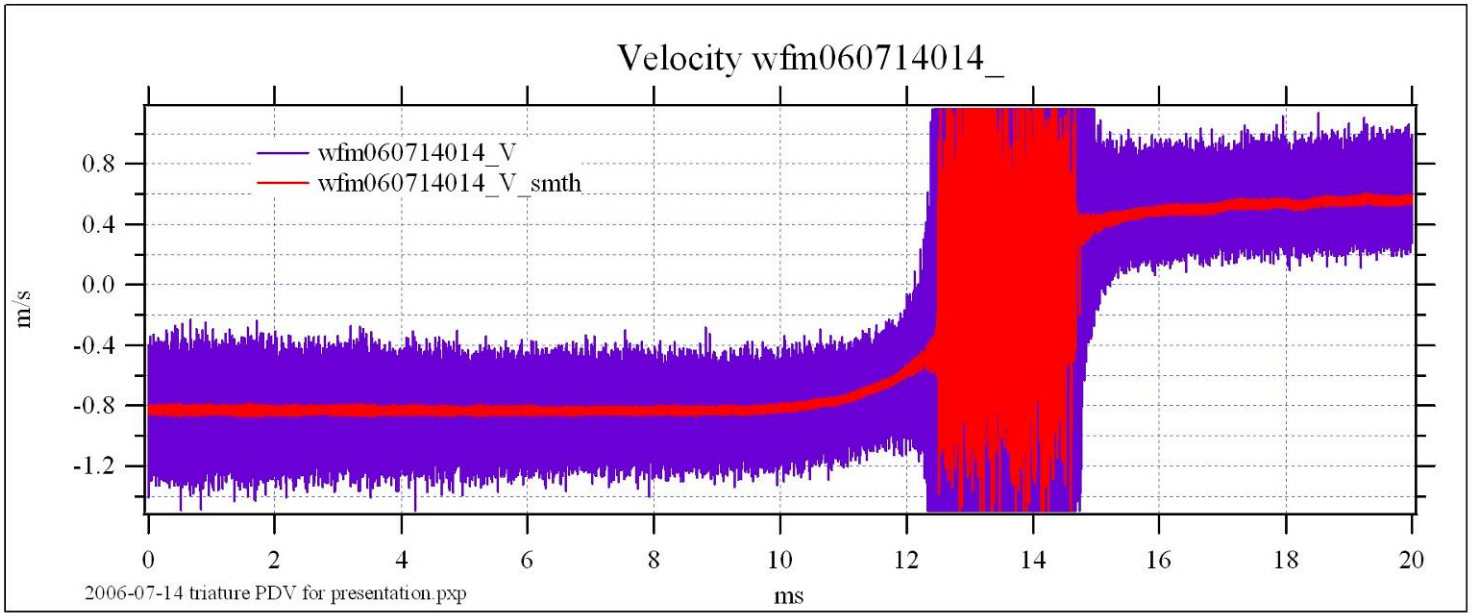




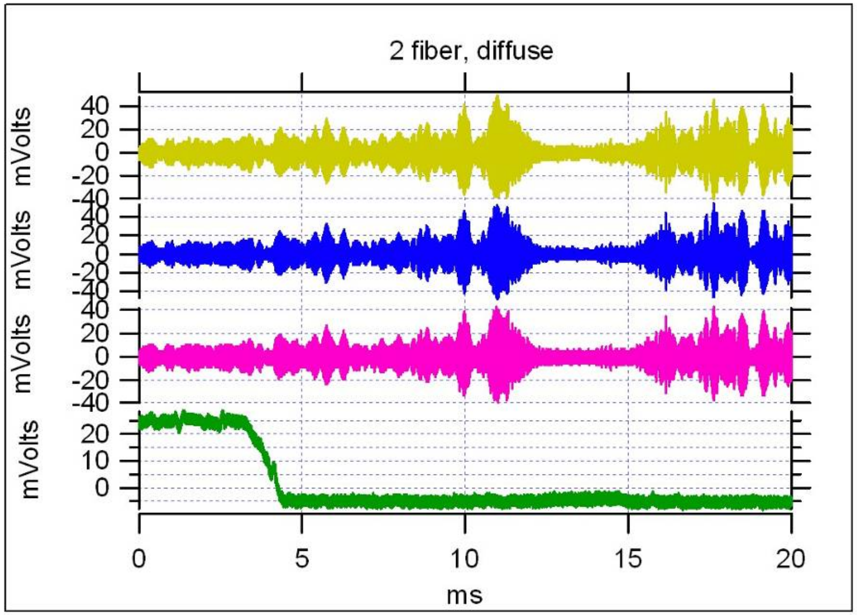


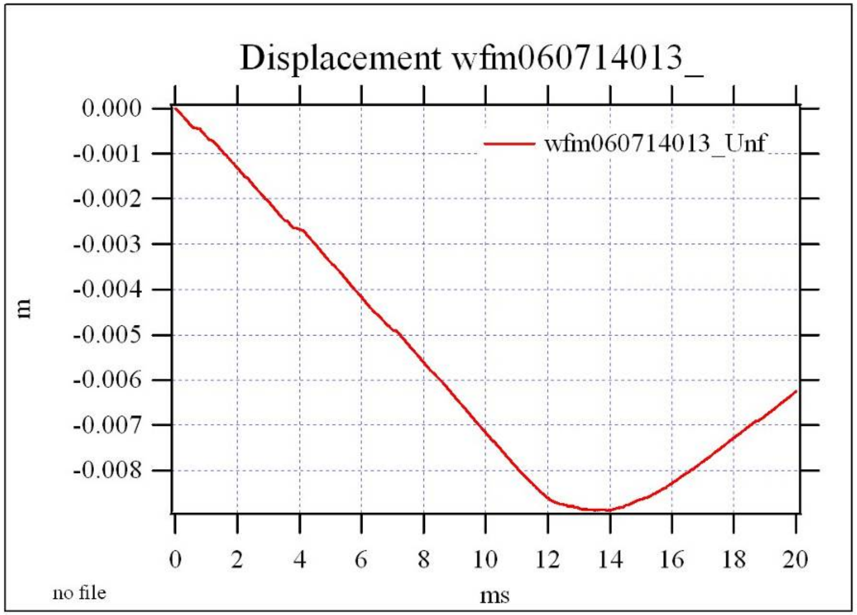
Quadrature PDV, Mirror target, two fiber probe

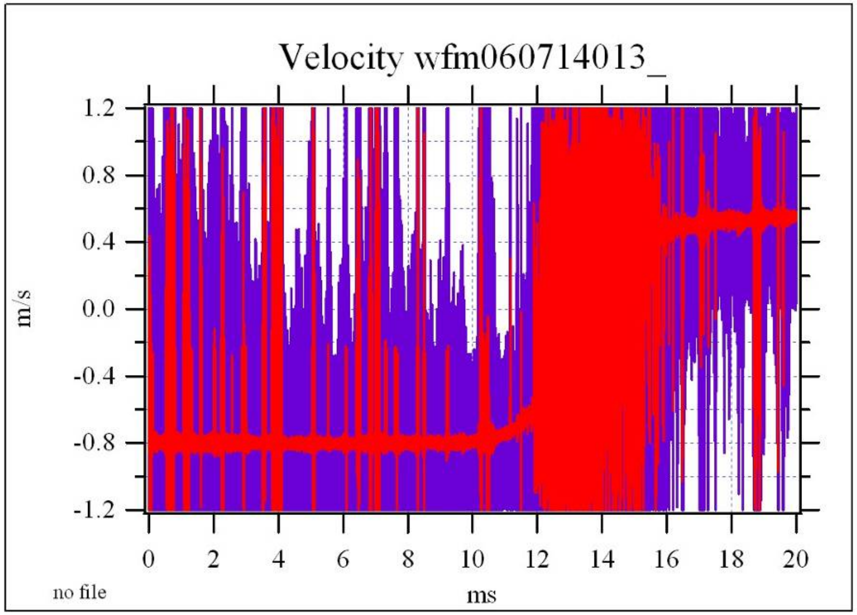


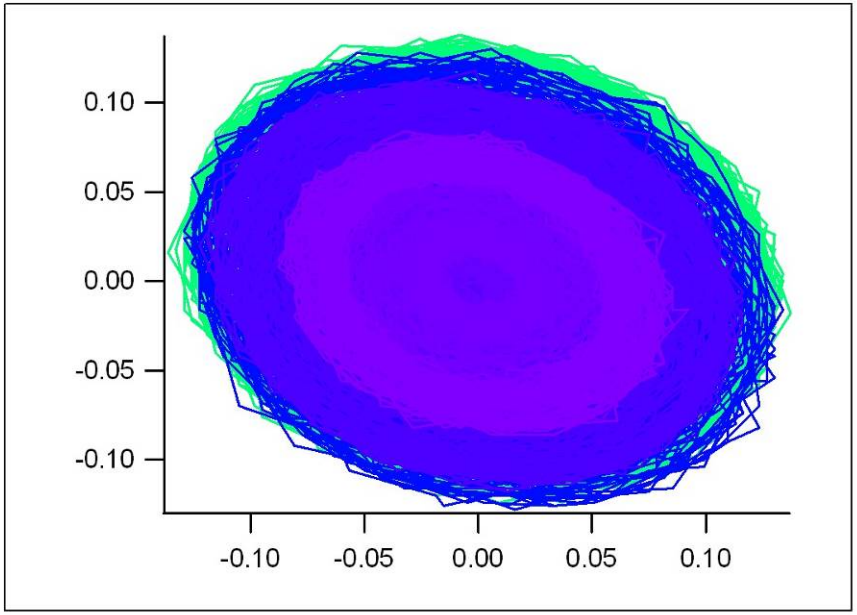


Quadrature PDV, bead blasted Aluminum target, two fiber probe

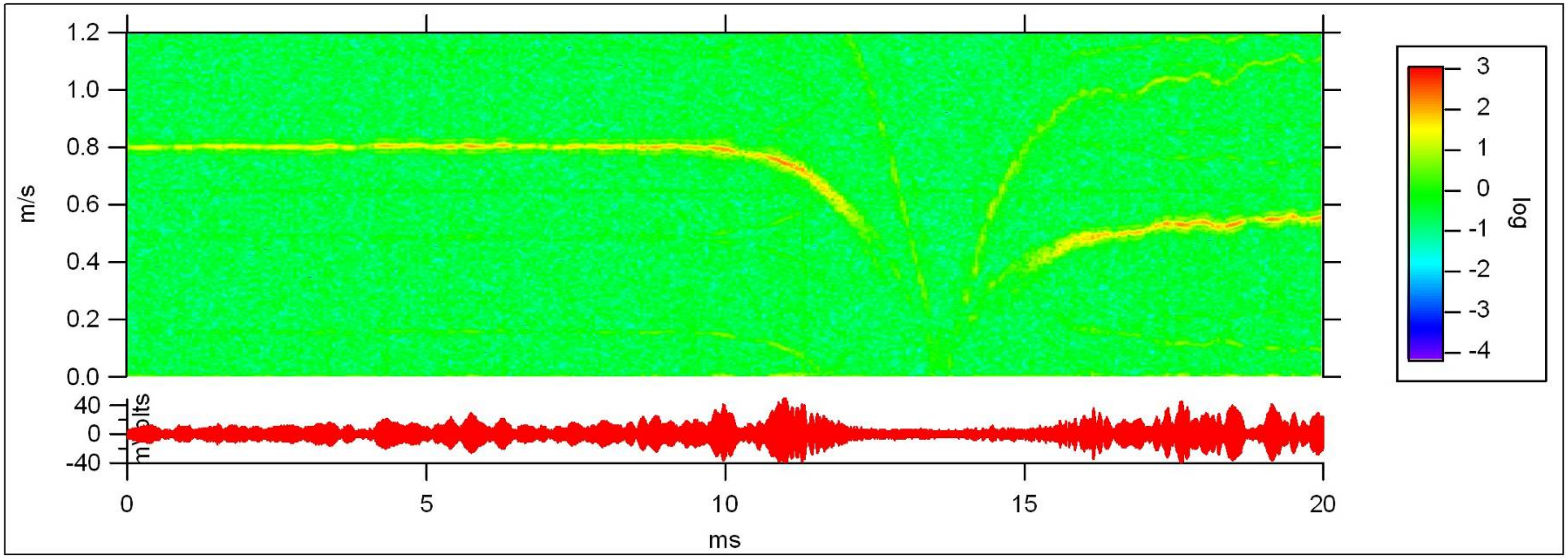


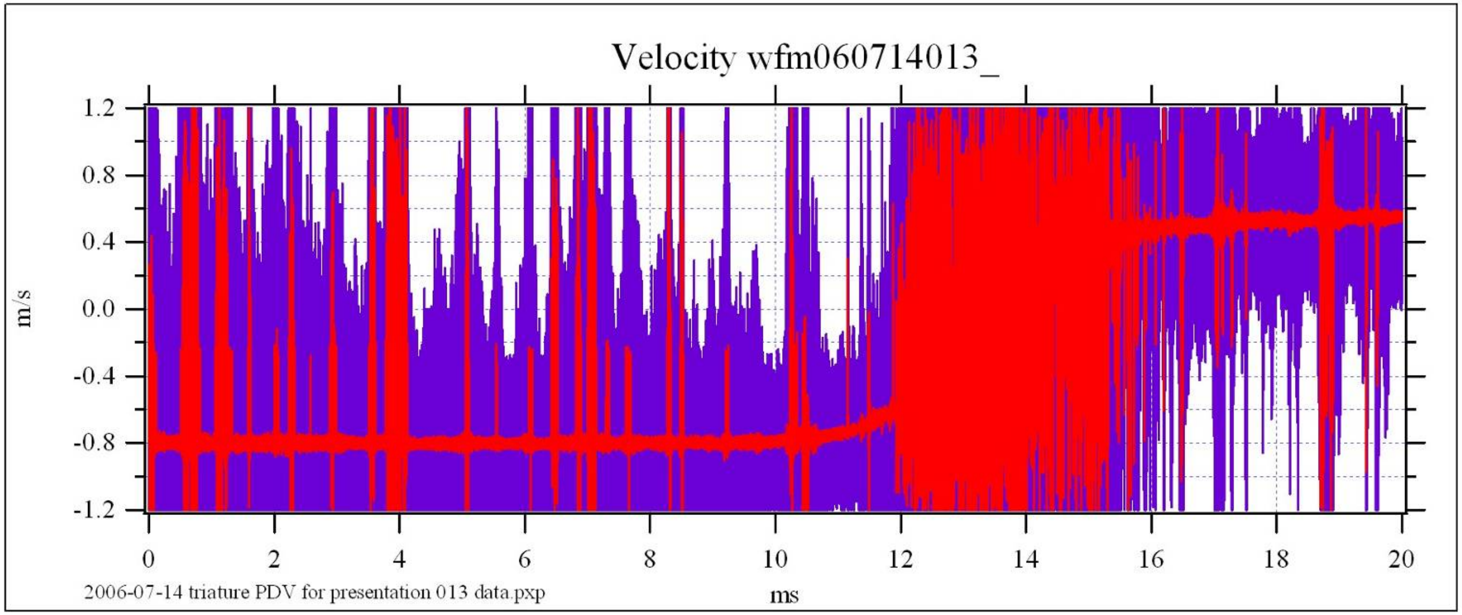




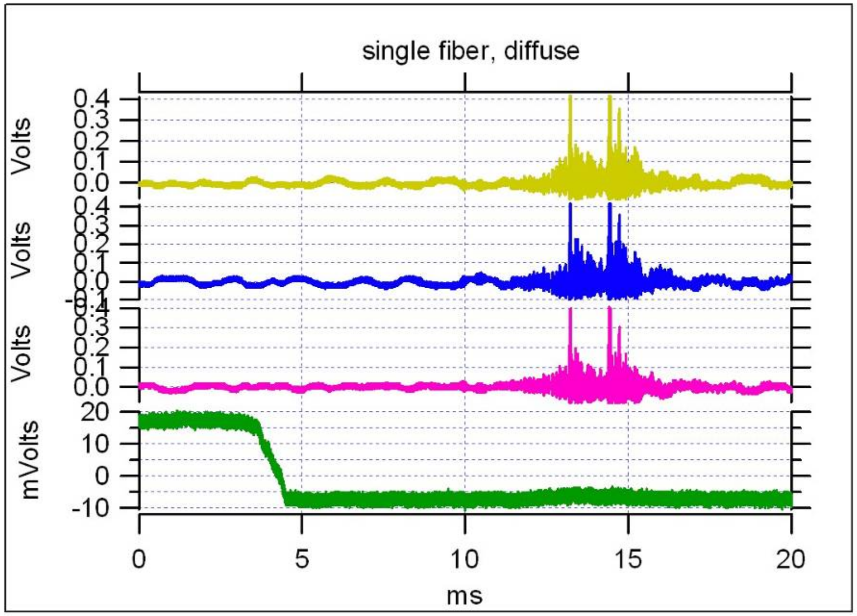


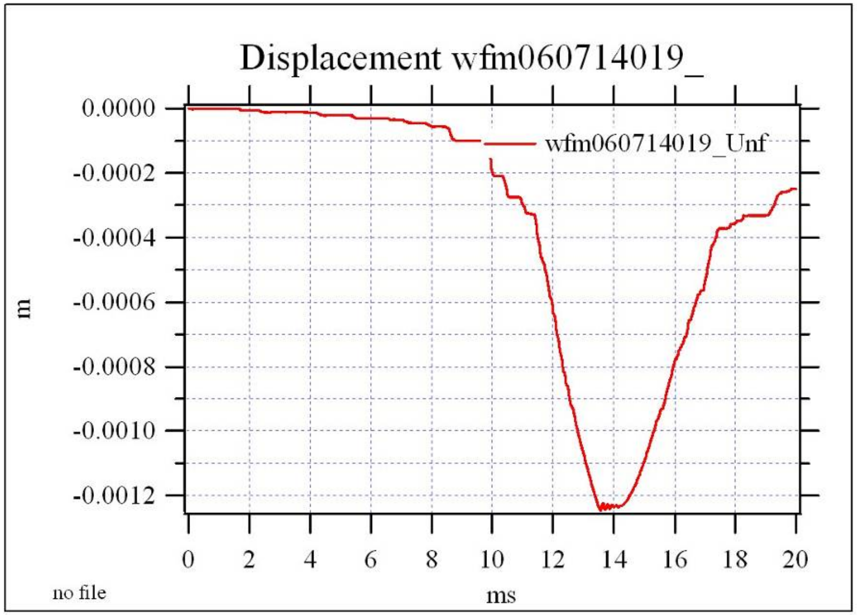
Quadrature PDV, bead blasted Aluminum target, two fiber probe

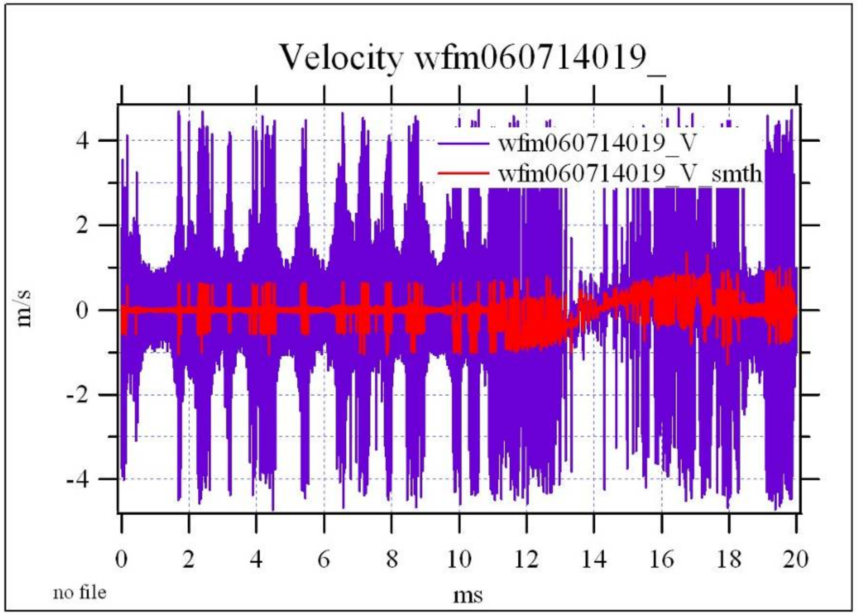


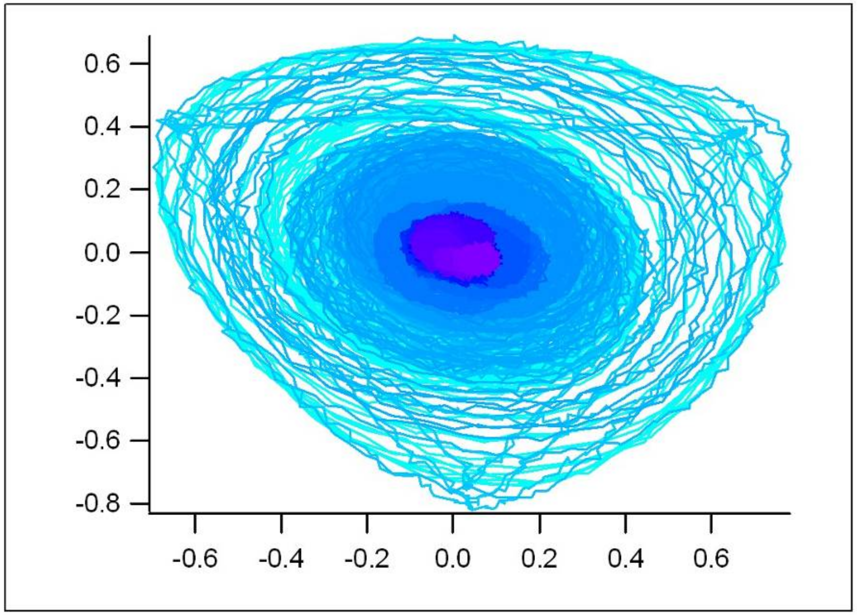


Quadrature PDV, bead blasted Aluminum target, single fiber probe

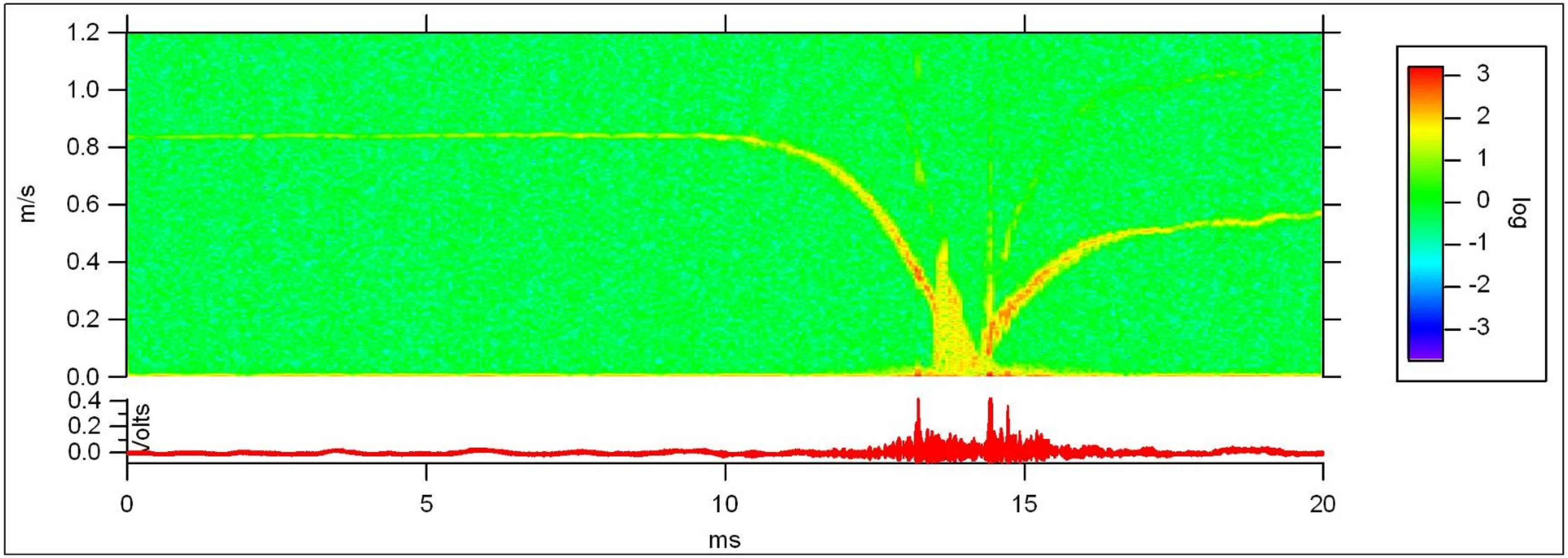


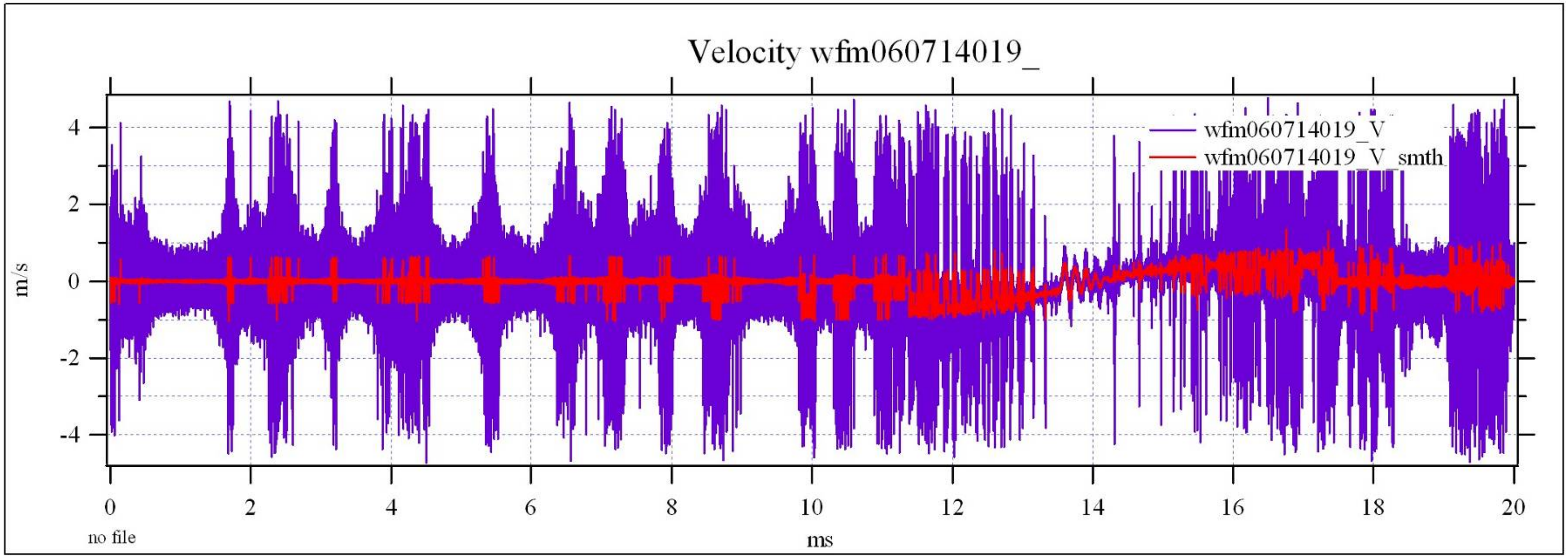






Quadrature PDV, bead blasted Aluminum target, single fiber probe

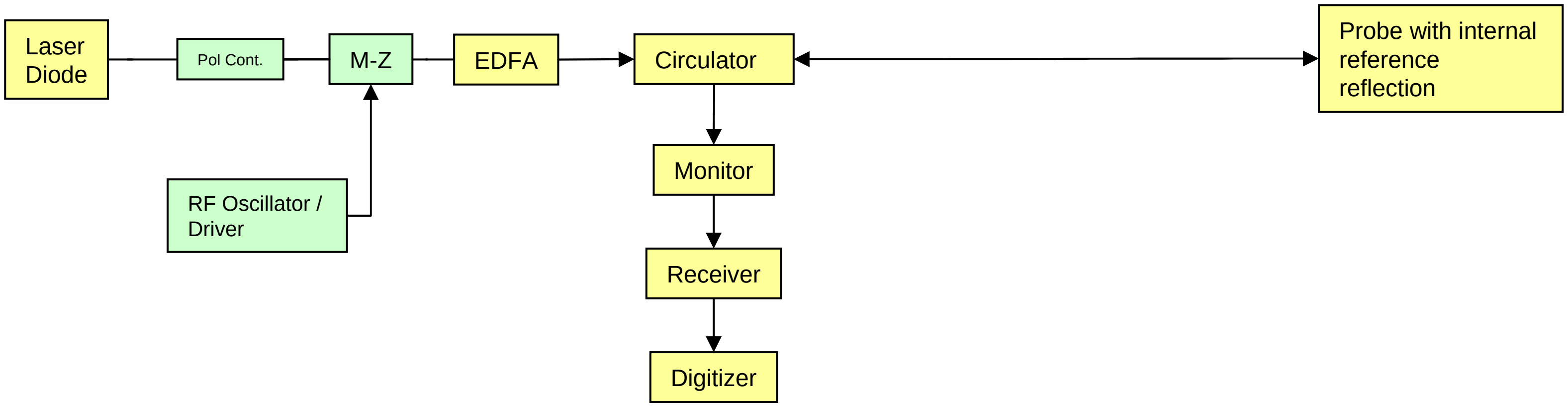




Heterodyne PDV Systems for Downconversion

- MZ heterodyne
  - Generate multiple sidebands that propagate to probe as well as reference
  - Very simple to implement – compatible with simplest PDV system
  - Extends the velocity range of a single recording channel, but with some ambiguity
- SSB modulator for single frequency shifted local oscillator
  - SSB modulator generates a single sideband for the reference beam.
  - Interferometer is more complex to implement due to splitting, coherence, and polarization.
- Phase modulator + filter
  - Ted Strand
- RF downconversion
  - I prefer lighter work!

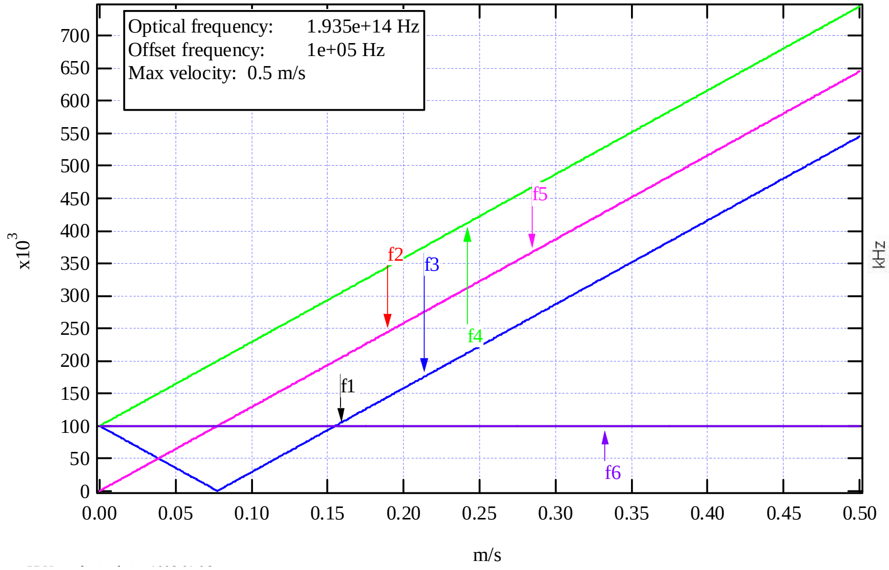
Simple Mach-Zehnder Heterodyne PDV with probe reference

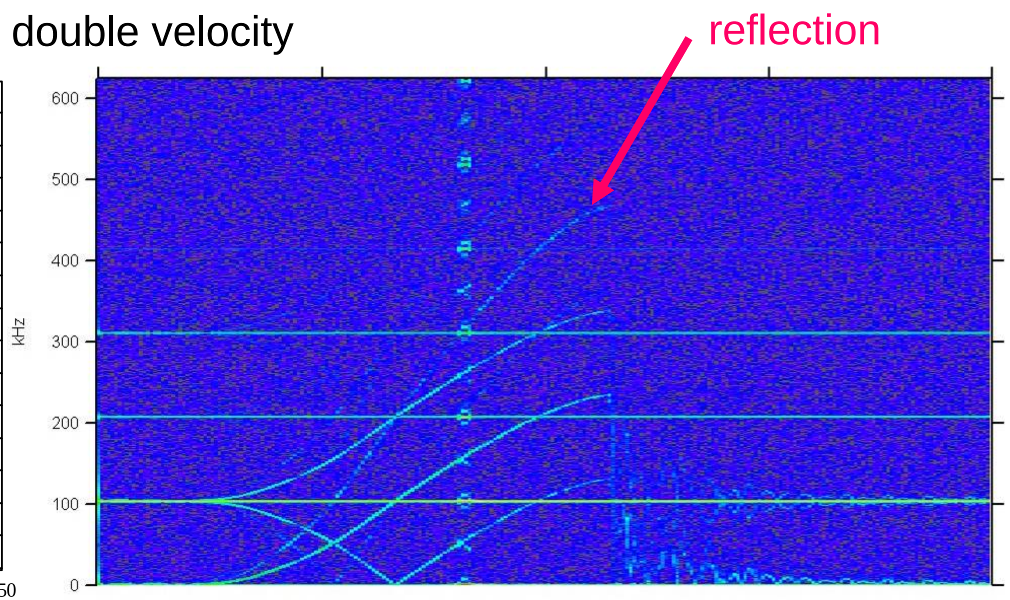


- Modulate the output of the seed laser to generate multiple sidebands.
- Sidebands are propagated in the shifted and reference light, producing multiple heterodyne frequencies.
- Compatible with simple PDV systems. No change in probe, receiver, detector, or basic analysis required.
- Results in some ambiguity in the data.

Mach-Zehnder Heterodyne System - Data

- Polished target on spring-loaded slide, moving ~0.2 m/s
- This shows the multiple heterodyne signals. Normally, the frequency would be chosen so that scope bandwidth would limit the observed signals to about ½ the local oscillator offset frequency
- A reflection from the probe end shows double velocity

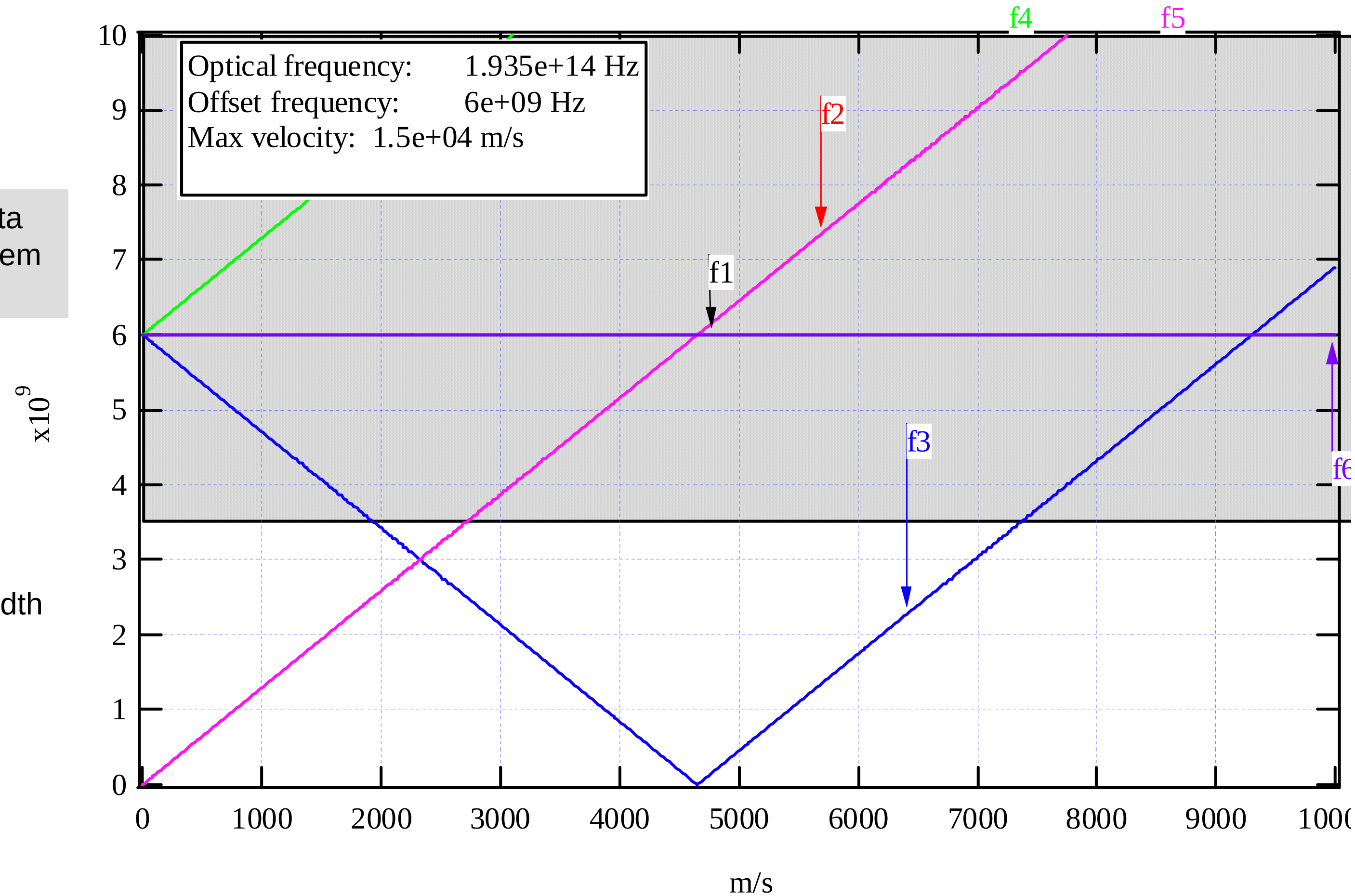




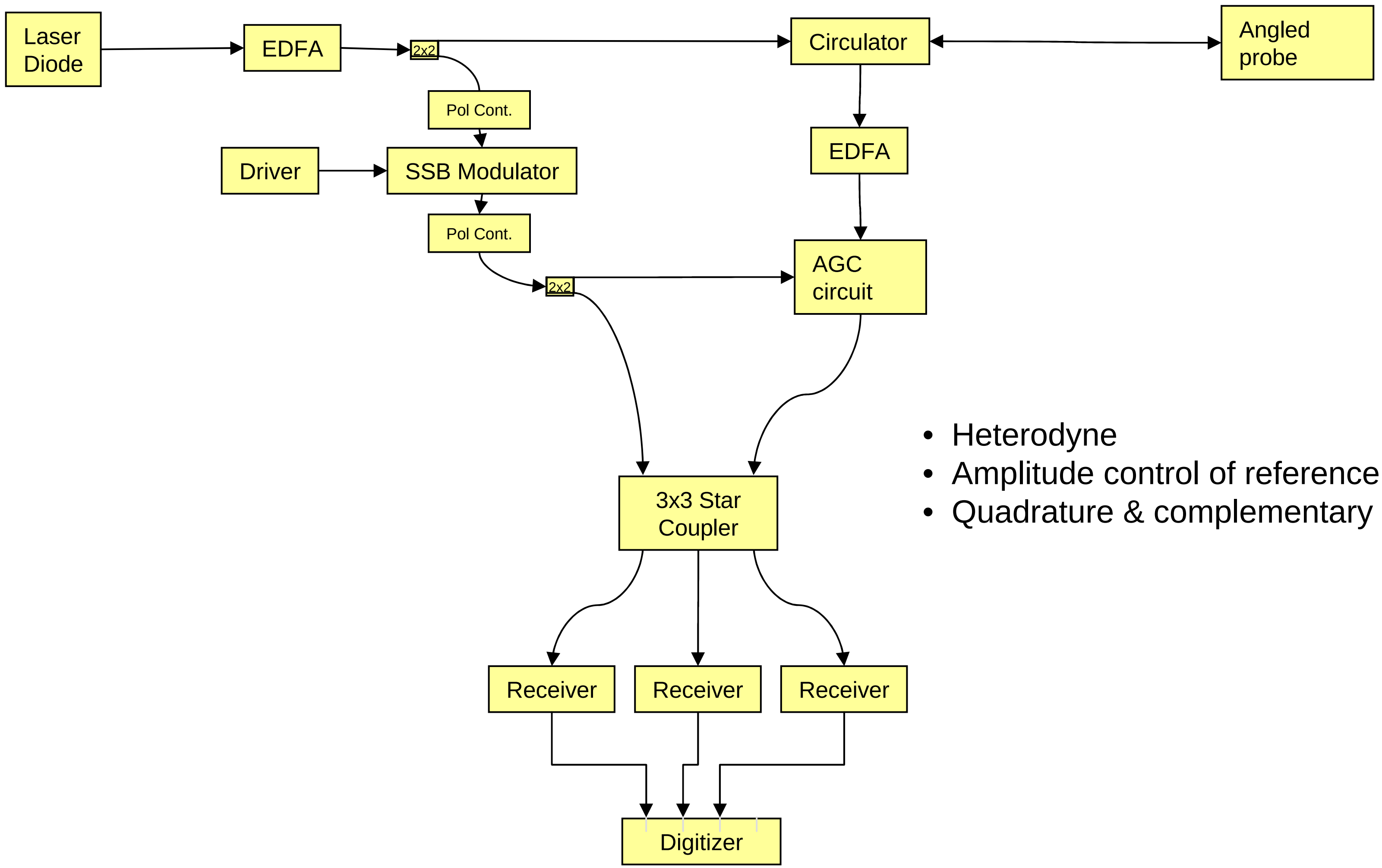
Calculated Heterodyne Frequencies show that a 3 GHz scope could record >7 km/sec

Shaded area indicates data outside the recording system bandwidth

Recording system bandwidth 3 GHz



Heterodyne 3x3 PDV with Shifted Local Oscillator using Single Sideband Modulator



- Heterodyne
- Amplitude control of reference
- Quadrature & complementary outputs

Single Sideband Optical Modulators

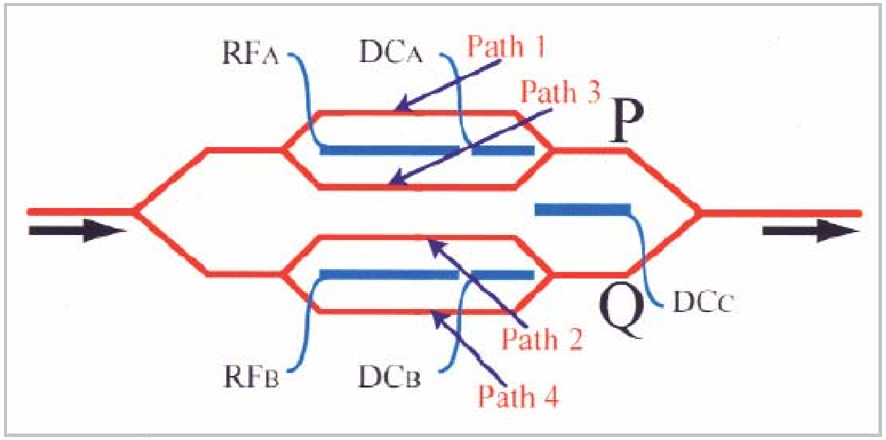


Fig.7 Optical SSB modulator

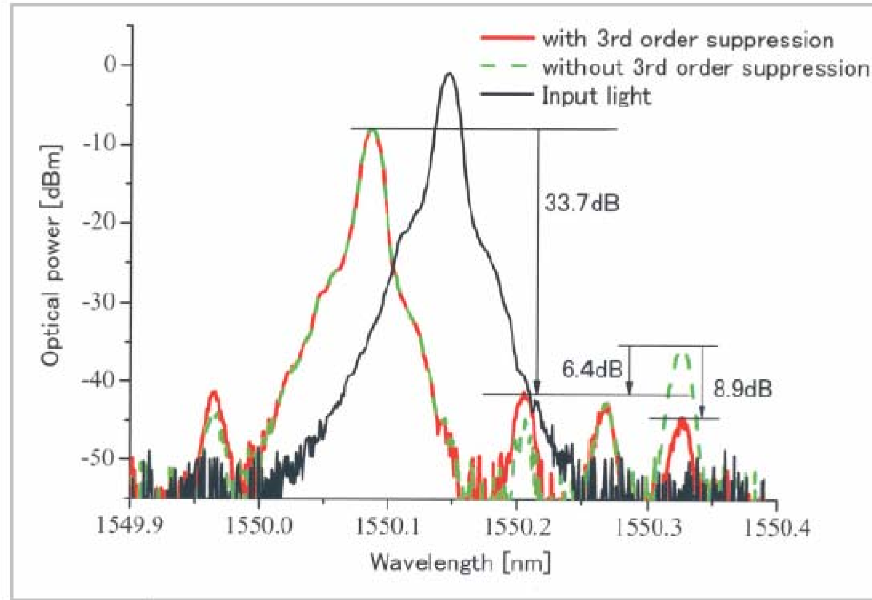
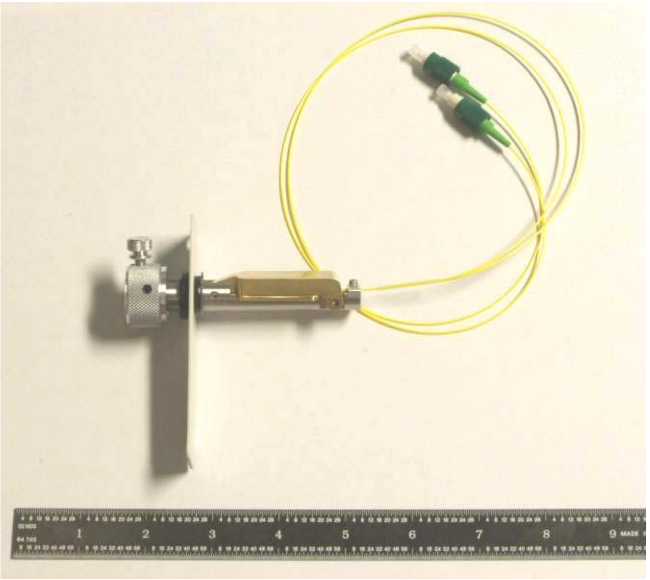
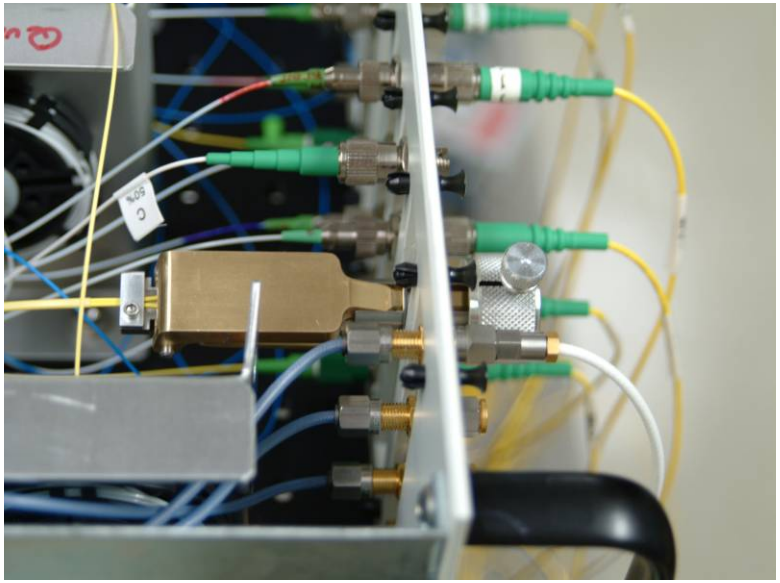


Fig.8 Spectrum of output light wave shifted by optical SSB modulator

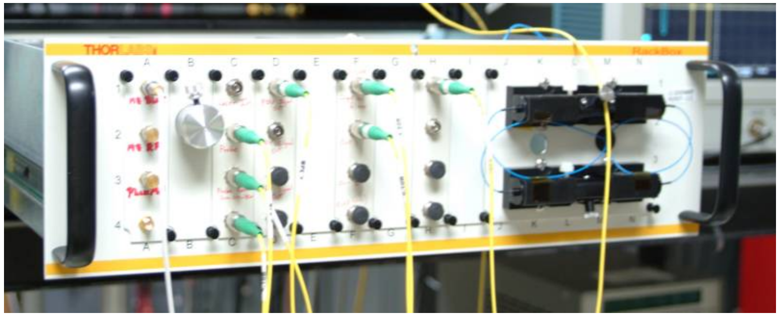
- **KAWANISHI Tetsuya and IZUTSU Masayuki, "Optical Modulators for Photonic Sideband Management",** ***Journal of the National Institute of Information and Communications Technology*** *Vol.51 Nos.1/2 2004, pp.41-50*

Panel-mounted Polarization Controller





Rotatable squeezer provides front panel adjustability in a very small space.



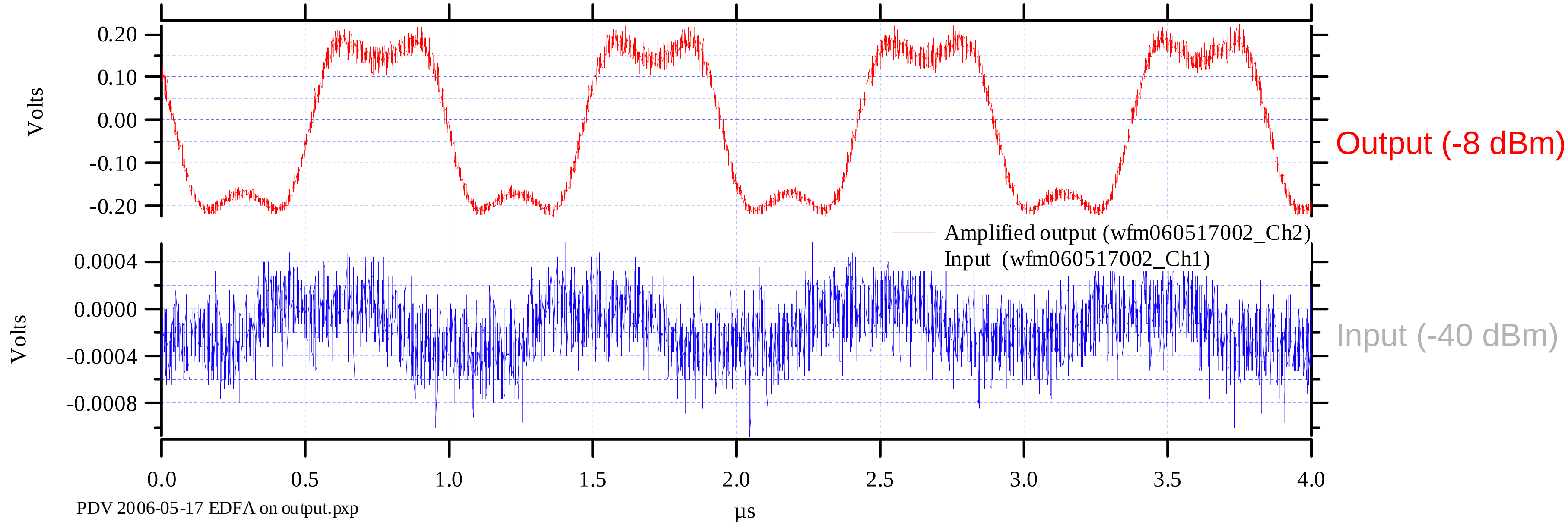
Signal improvement & noise reduction

- EDFA on output
  - 30 dB gain
  - Raises signals to levels that allow AGC and other techniques
  - Noise figure ~5 dB
  - May reduce the need for high power lasers and help avoid Brillouin scattering in the input fiber.
- Automatic Gain Control – equipment hasn't arrived
  - Apply to shifted light to try to maintain constant fringe amplitude
  - Boston Applied Technologies Optical Power Regulator
- Thin etalon in probe for tunable reference beam
  - ~150 µm thick glass plate in beam from probe
  - Tune laser wavelength for desired reference level
  - Doesn't allow quadrature
- Speckle mitigation – multiple receive or send fibers, λ multiplexing, multimode fibers
  - Multiple receive fibers give overlapping coverage

EDFA to amplify shifted light

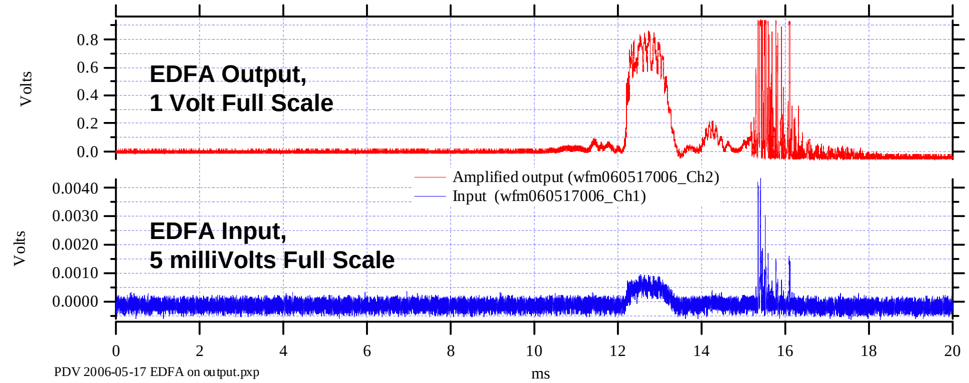
Amonics AEDFA-LP

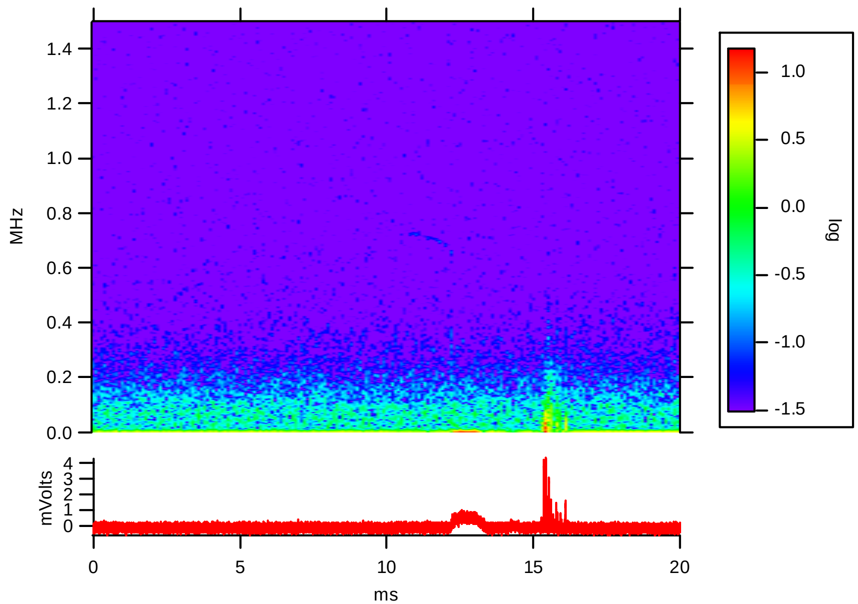
Saturation Output Power (at –3dBm input signal)	>+13 dBm
Small-Signal gain at 1550nm (at -30 dBm input signal)	>30 dB
Noise Figure (typ.) (at -3 dBm input signal)	5.0 dB
Operating Wavelength	1528 nm – 1565 nm



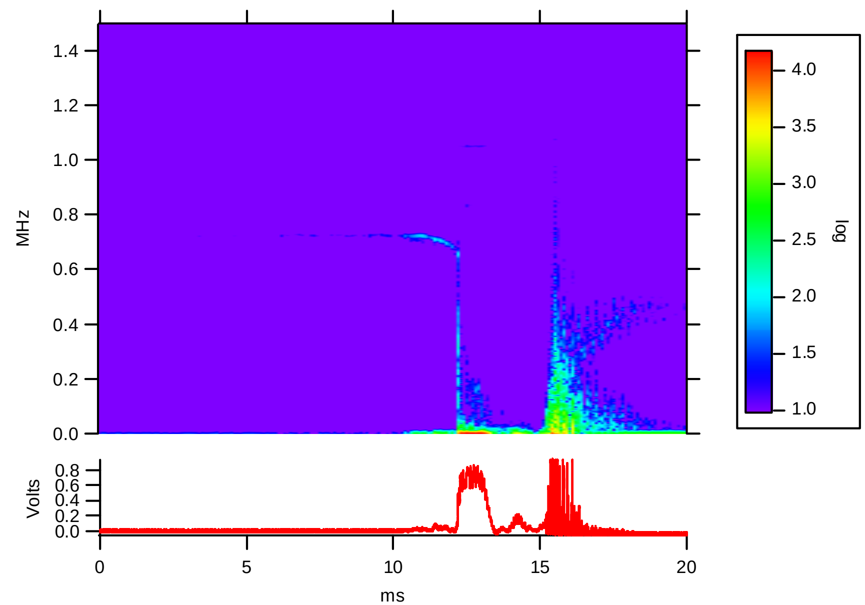
PDV fringes amplified by EDFA

2 mW input laser power,
bead blasted target surface,
bare fiber probe





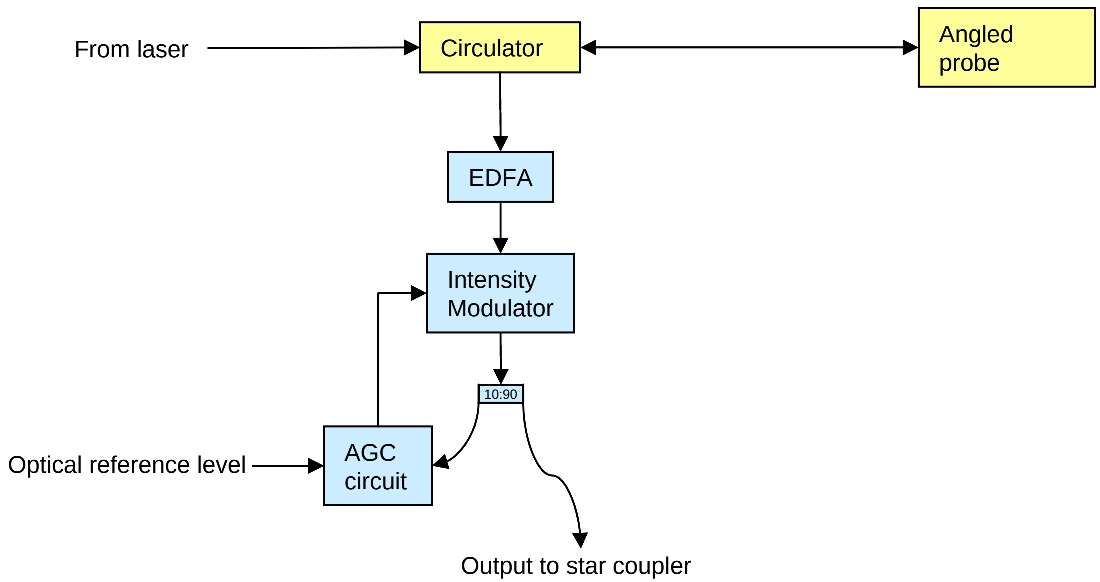
Unamplified signal



Amplified signal

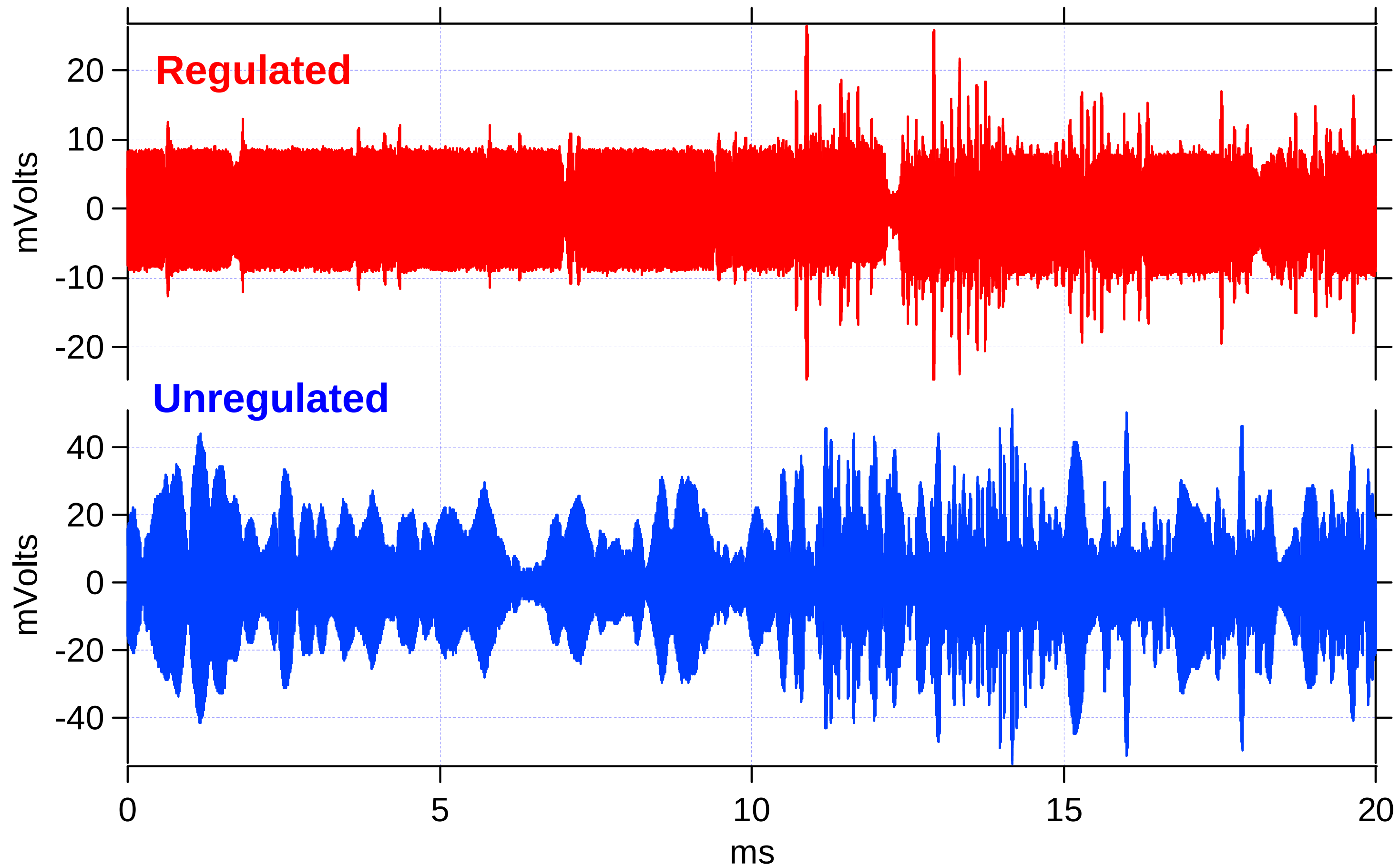
Automatic Gain Control

- Reduce the fluctuations in the shifted light.
- Boston Applied Technologies Optical Power Regulator
- Is it fast enough?
- Will is cause artifacts?



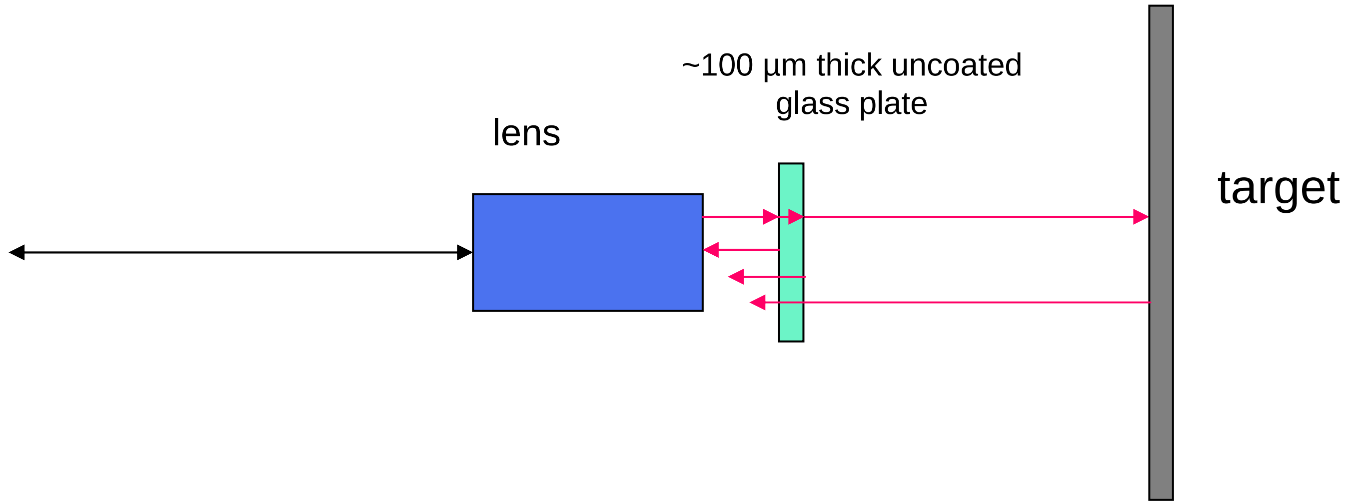
Optical Power Regulator

- Boston Applied Technologies
- ~300 ns response time
- Bare fiber probe with retroreflector target



Thin etalon for wavelength-tunable reference beam

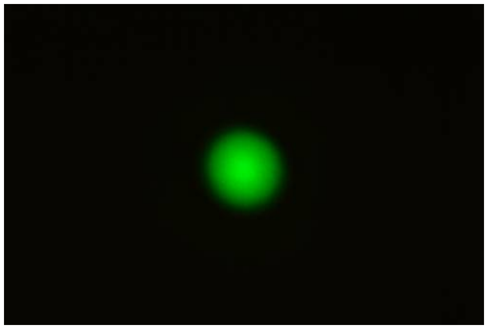
- Thin plate makes tuning relatively insensitive to wavelength so the Doppler shift will not result in amplitude modulation when the light is transmitted through the plate.
- Light reflected from front and back surfaces of glass plate interferes, so reference signal varies sinusoidally with wavelength of laser



Speckle Mitigation

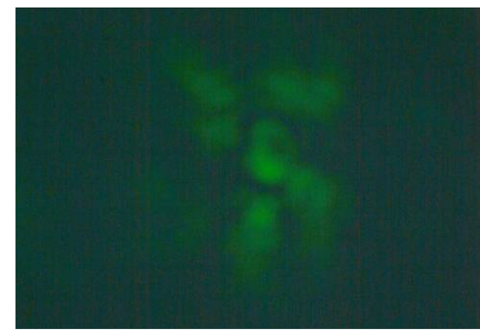
- Fringe visibility fluctuation is primarily driven by coupling of scattered light into a single mode fiber.
- Sampling the speckle pattern at two points should give overlapping coverage, particularly if the two collection fibers are separated by ½ of the speckle size.
- For multimode fiber, you have to look at the overlap of the returning wavefront with the reference wavefront. If the light is distributed into many modes and polarizations, the fringe contrast will be poor. Therefore, restrict the launch light to low order modes.

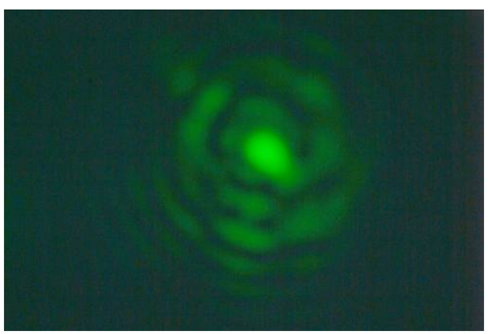
Interference patterns



SMF Gaussian beam

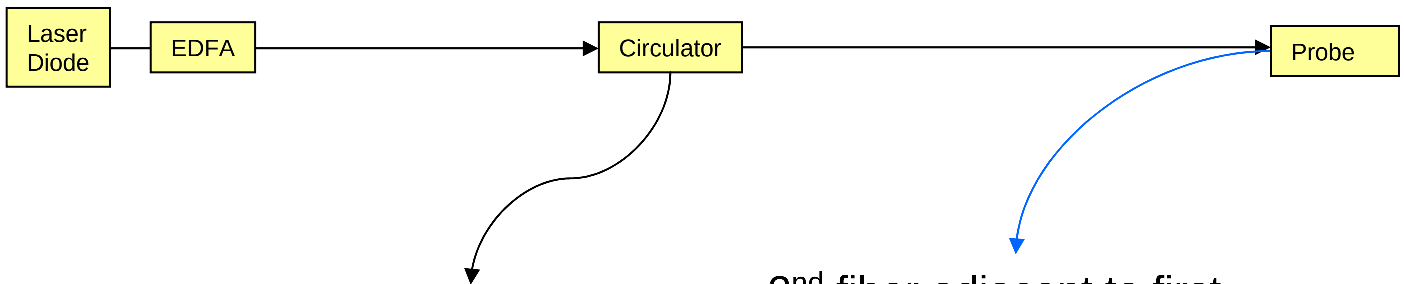
Speckle pattern from rough surface





Combined interference pattern

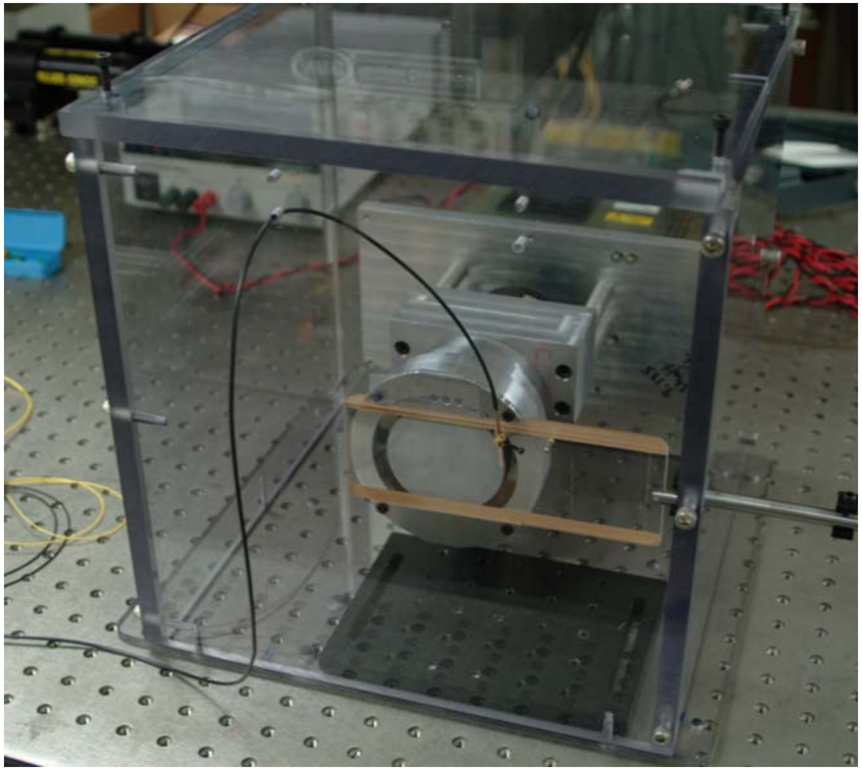
Probes for speckle mitigation



Conventional output

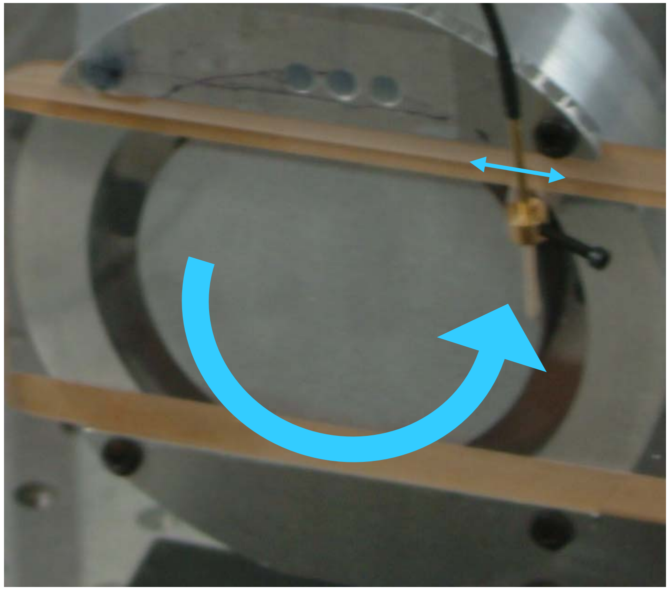
2^{nd} fiber adjacent to first samples a different point in the speckle pattern

Rotating Disk Test Stand

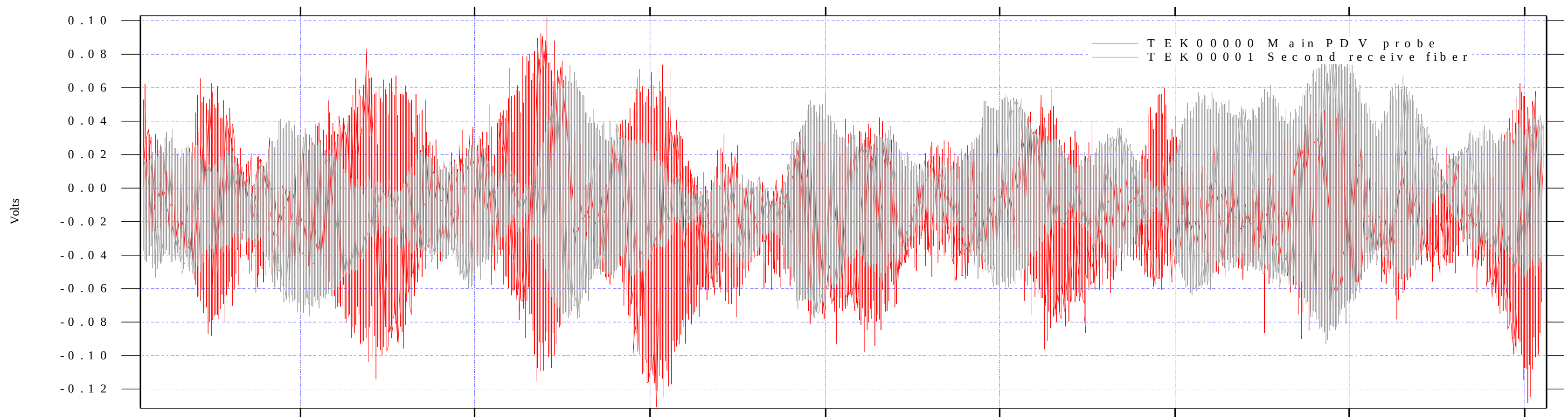


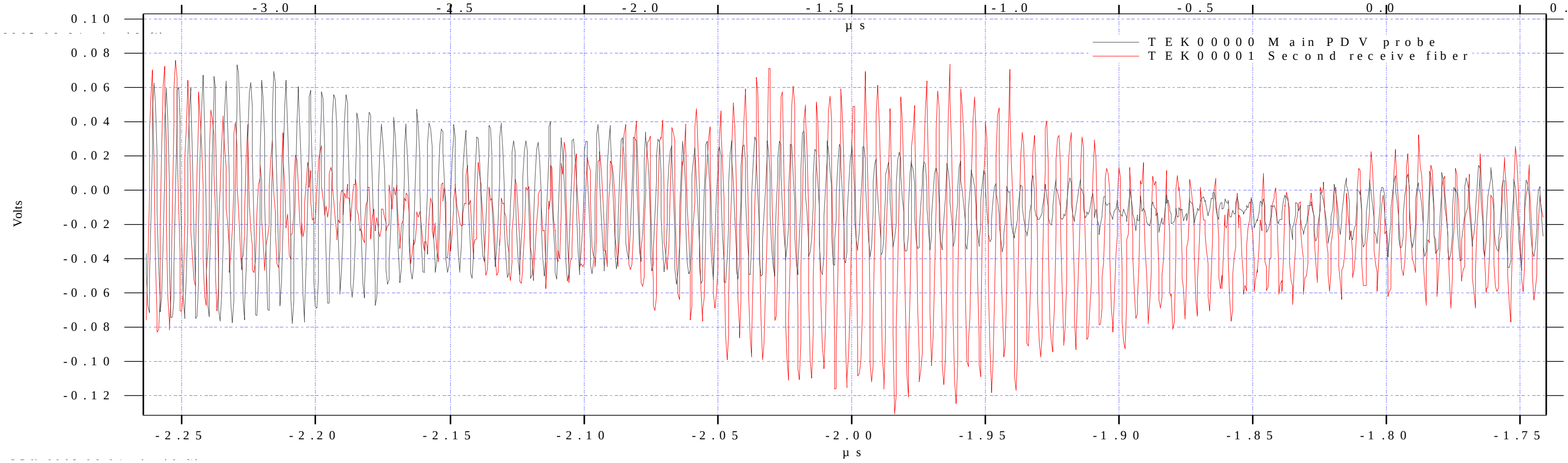
50,000 RPM, 175 m/s

Probe views surface at 80° angle of incidence and translates across the diameter of the disk to obtain velocities ranging from -175 m/s to +175 m/s.



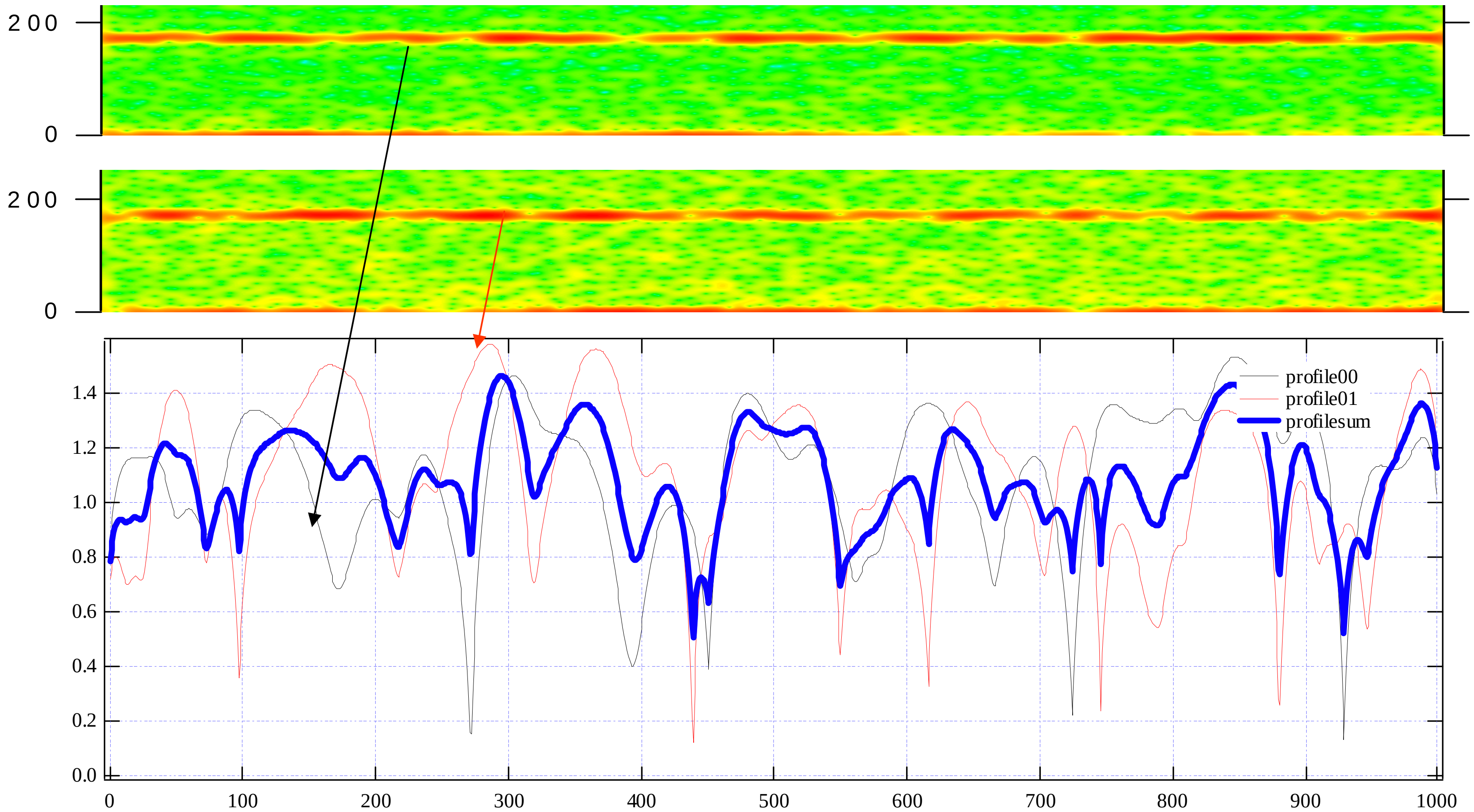
Dual receive fiber PDV data





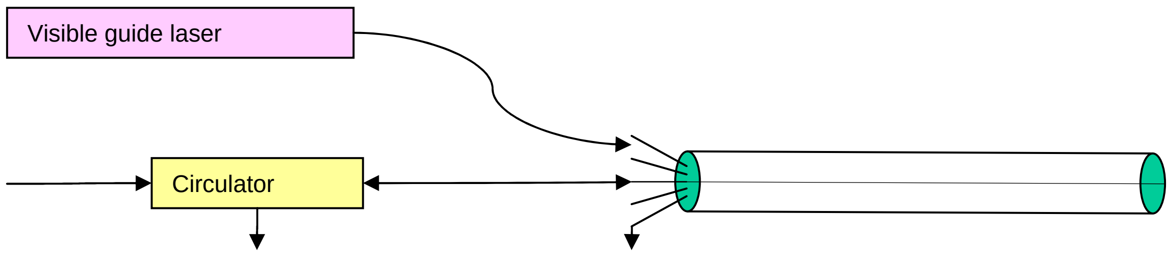
Combined data profiles

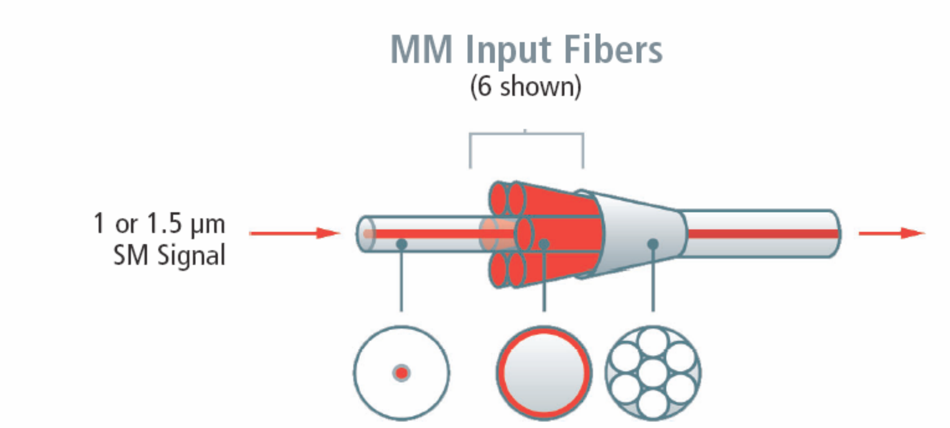
The fluctuations of the two PDV channels do not coincide, so the combined data has less variability.



Concentric Dual-Clad Fiber Probe

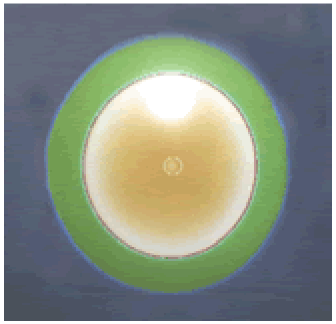
- Deliver light through SMF core.
- Collect light from MMF outer core as well as SMF inner core





OFS Power Combiner

- SM: 10 µm, 0.15 NA
- MM: 105 µm , 0.165 NA

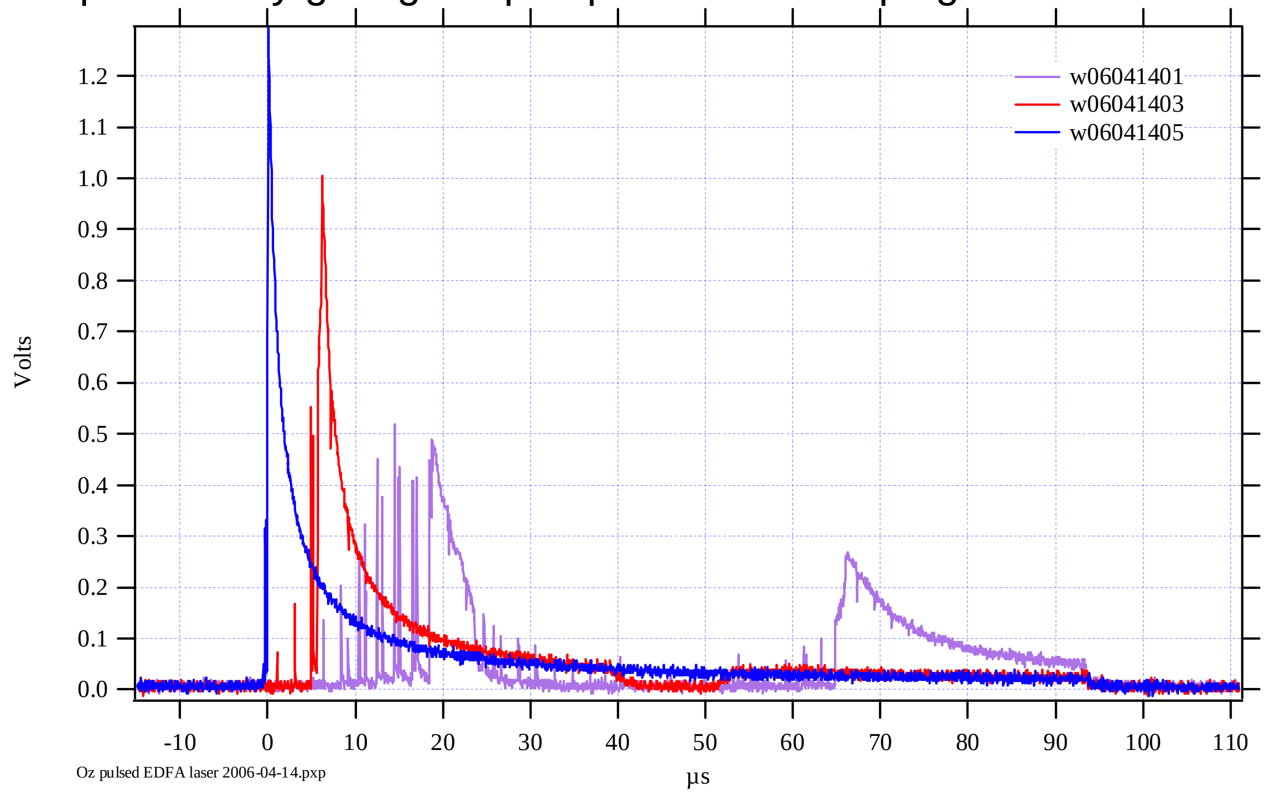


Fibercore SMM900

- SMF 6 µm, 0.19 NA inner core
- 90 µm, 0.23 NA outer core
- 5 dB/km @ 1.55 µm

High power pulsed laser for multiple channels

- Goal: 100 W, 100 µsec rectangular pulse
- I tried unsuccessfully to flatten the pulse by changing the seed laser drive pulse shape. Limited by erbium dynamics
- May be possible by gating the pump laser and shaping the seed laser



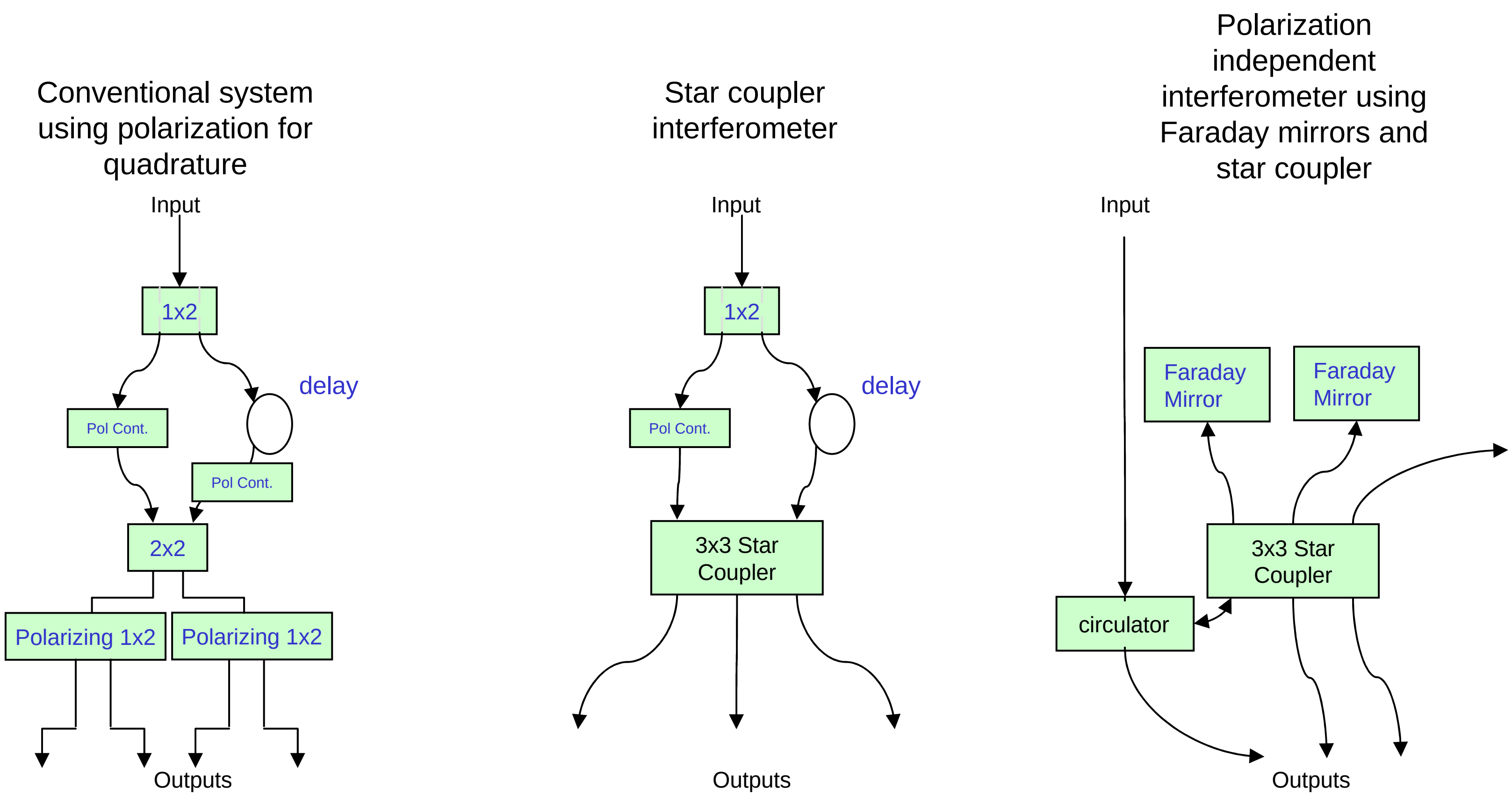
Velocity Interferometer

- Singlemode fiber delay interferometer.
- Fringe phase proportional to velocity.
- Not a VISAR because it's singlemode.

- No unshifted light allowed! This restricts the PDV configurations if you want to share the same light.
- Singlemode VISAR may not work well on non-specular surfaces because there is not the "gain" that occurs in PDV when the shifted light is mixed with the local oscillator.

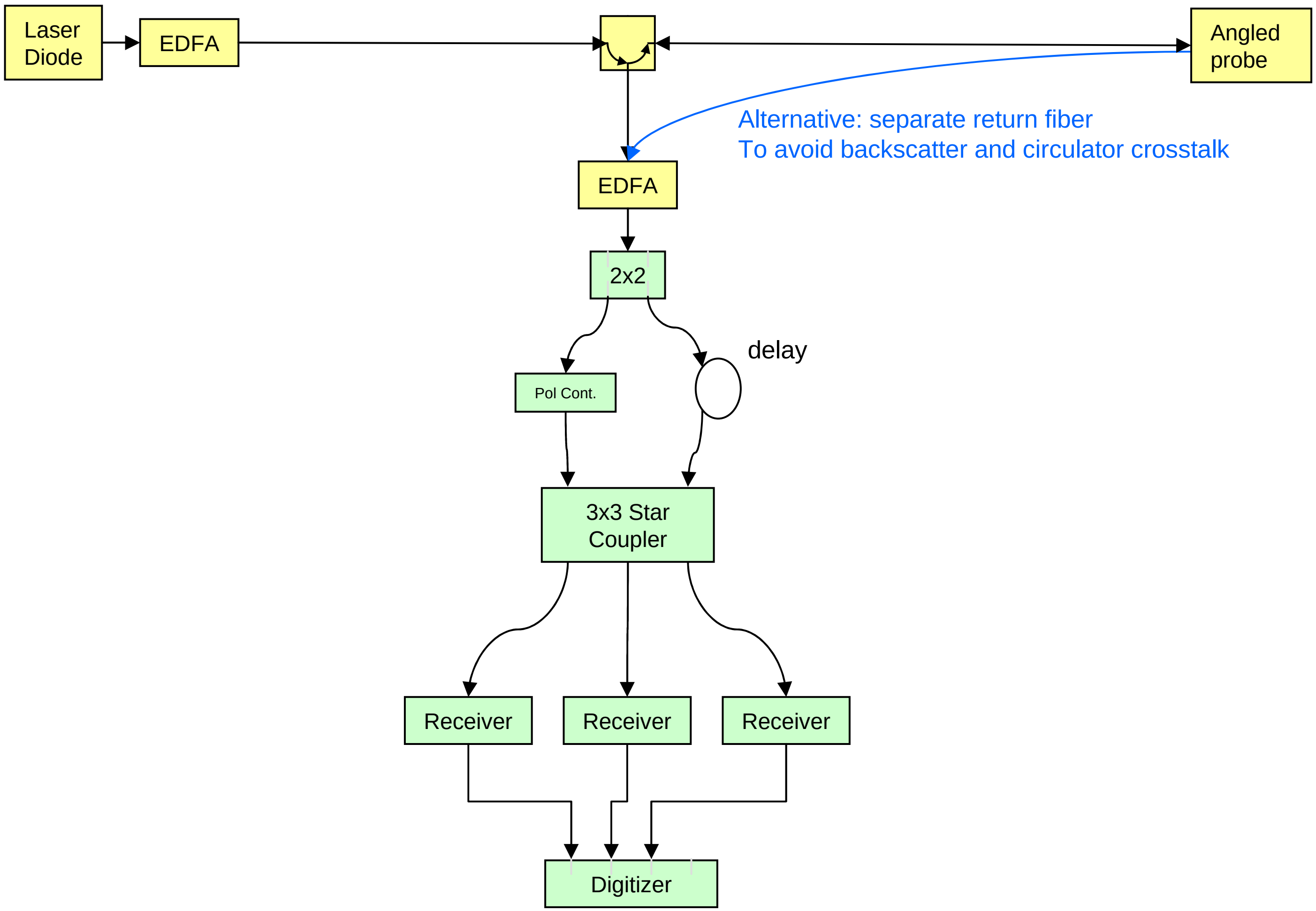
- Quadrature outputs via 3x3 or 4x4 star coupler, or bulk optics.
- A multimode bulk optic 1550 nm VISAR could use light collected by an adjacent multimode fiber in the probe.

Singlemode Velocity Interferometer Configurations



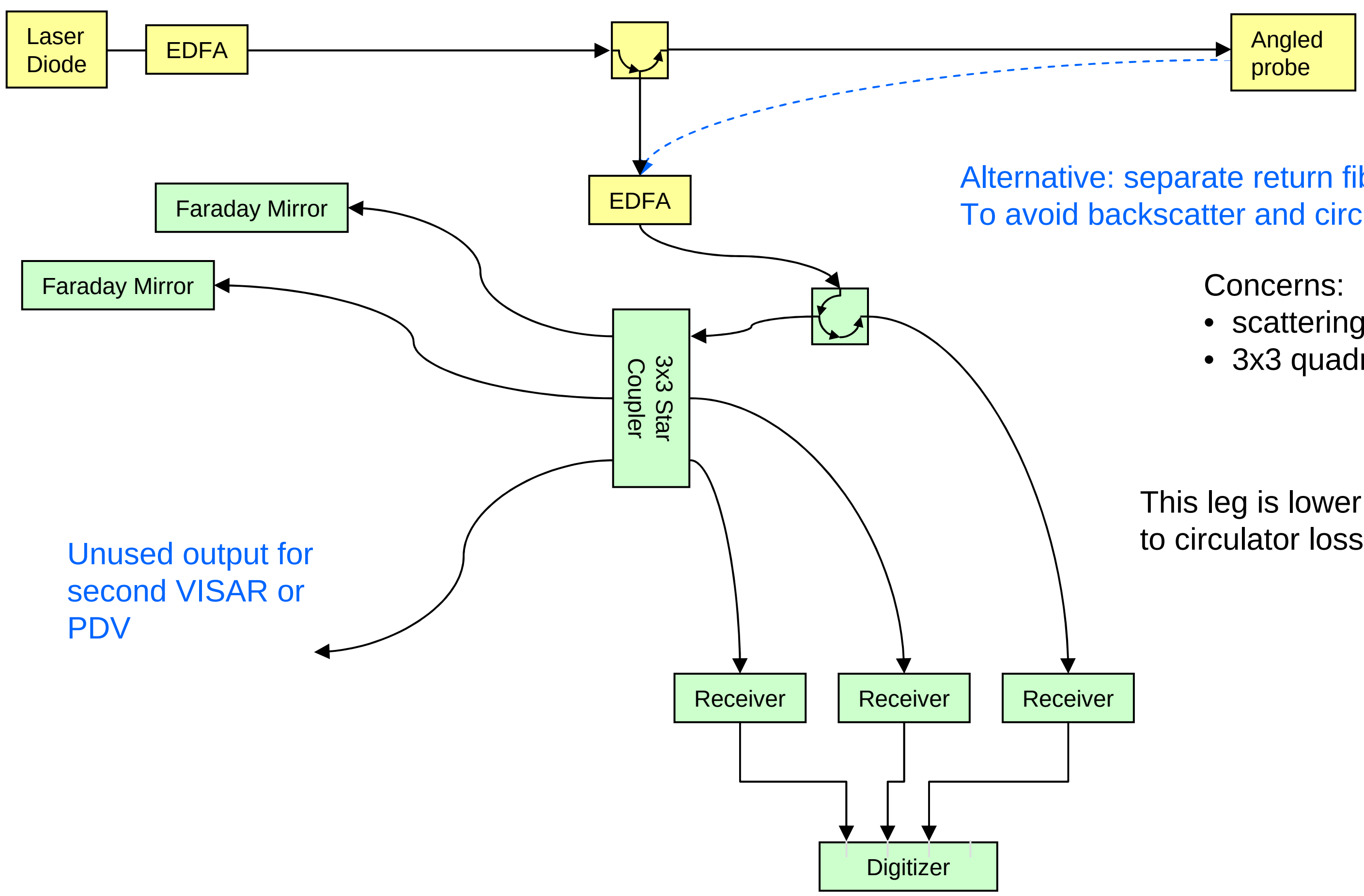
SMF Velocity Interferometer

using 3x3 star coupler



3x3 Velocity Interferometer

using Faraday mirrors



Alternative: separate return fiber
To avoid backscatter and circulator crosstalk

Concerns:

- scattering in single fiber probe
- 3x3 quadrature performance

This leg is lower amplitude due to circulator loss.

Combination PDV + Velocity Interferometer