



# PDV Systems and Cost Reductions

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# Agenda

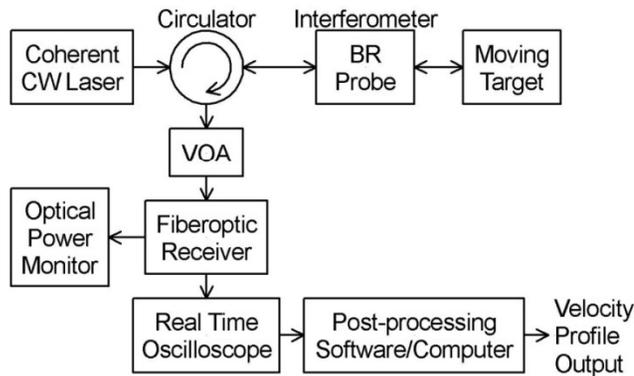
- Classical Photonic Doppler Velocimeter (PDV) Systems
- Example PDV equipment costs
- Spotting Laser
- Lasers, Coherence, and Optically Amplified Lasers
- Interferometry approximation for PDV
- Special Amplifiers and Frequency Dividers
- Counters with DAC and/or RAM
- Single Box PDV systems
- Food for Thought
- Conclusion

# PDV Systems Review

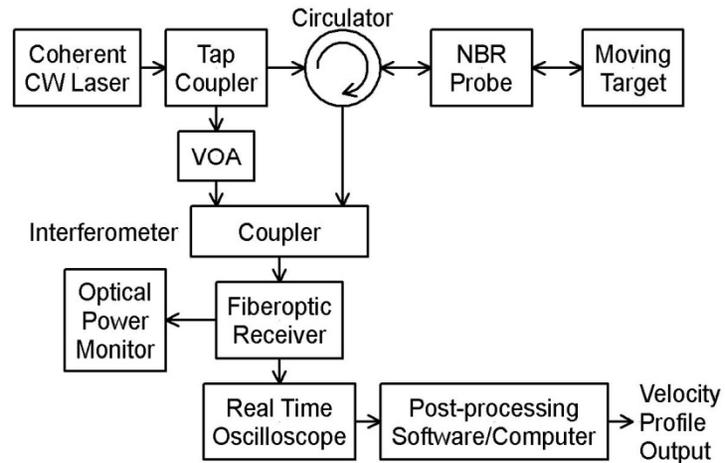
- Technology developed for over a decade, based on century old science
  - Well established, very successful, a material science renaissance!
  - Non-contact measurement of position, velocity, acceleration, and jerk possible
  - Based on optical interferometry, inherently position based, sub-micron resolution
  - “It’s all over” in typically 100 ns, 100 us, or 100 ms, depending on experiment
- Systems produced within PDV community
  - Typically use off-the-shelf components for availability (rarely used in telecom industry)
  - Commercial equipment emerging using industrial telecom components
- Basic classical PDV system consists of:
  - Continuous wave (CW) coherent laser source
  - Fiber optic components (circulator, couplers, attenuator)
    - Depends on probe type
    - Multi-way splitter of laser source often used in multi-channel systems
  - Probe, either Back-Reflecting (BR) or Non-Back-Reflecting (NBR) type
  - Moving target (the experiment!)
  - Fiber optic receiver (PIN or APD, AC or DC coupled) and input power monitor
  - Real-time oscilloscope
  - Oscilloscope trigger input (usually from experimental setup)
  - Post-processing software and computer (outputs velocity profile of target)

# Classical Single-Channel PDV Systems and Performance

Back-Reflecting (BR) Probe type



Non-Back-Reflecting (NBR) Probe type



Typical system losses (1550 nm, VOA=0)

- Laser to probe tip (glass side) = 1 dB (20.6%)
- Probe BR of laser to ORX (Fresnel) = 14 dB (96%)
- Probe tip (glass side) to ORX = 2 dB (36.9%)
- PIN = -19 dBm (12.6 uw) sensitivity, 0 dBm overload
- APD = -25 dBm (3.2 uw) sensitivity, -7 dBm overload
- ORX roll-off for AC coupling = 35 KHz → 3mm/s

Example with 500 mw laser into circulator

- BR probe emits 377 mw to air (20.6+4=24.6% loss)
- Laser BR at probe (→ ORX) = 20 mw (4%), +13 dBm
- Set VOA, ORX overload = 11 dB (PIN), 18 dB (APD)
- Min. target reflection, PIN ORX = -6 dBm (251 uw)
- Min. target reflection, APD ORX = -5 dBm (316 uw)
- Min. probe efficiency = 0.05% (PIN), 0.06% (APD)

Typical system losses (1550 nm, VOA=0)

- Laser to probe tip (glass side) = 1.2 dB (24.1%)
- Laser to ORX (via coupler tap) = 23 dB (99.5%)
- Probe tip (glass side) to ORX = 4.5 dB (64.5%)
- PIN = -19 dBm (12.6 uw) sensitivity, 0 dBm overload
- APD = -25 dBm (3.2 uw) sensitivity, -7 dBm overload
- ORX roll-off for AC coupling = 35 KHz → 3mm/s

Example with 500 mw laser into tap coupler

- NBR probe emits 380 mw to air (24.1% loss)
- Laser to ORX (tap coupler) = 2.5 mw (0.5%) = +4 dBm
- Set VOA, ORX overload = 4 dB (PIN), 11 dB (APD)
- Min. target reflection, PIN ORX = -10.5 dBm (89 uw)
- Min. target reflection, APD ORX = -9.5 dBm (112 uw)
- Min. probe efficiency = 0.018% (PIN), 0.022% (APD)

# Example PDV Equipment Costs

Fiber ring laser source (2 watt) > \$20K

High speed real time oscilloscope (10 gig) > \$100K

Post-processing software/computer > \$3K plus S/W NRE plus S/W per copy cost

BR probe cost < \$100, NBR probe cost >\$100 to \$thousands

Other costs = packaging, cabling, trigger source

PDV Receiver ModBlock Types

Model Number	Receiver Type	RF Output Coupling	Probe Type	Spotting Laser?	Price Each
F170A-AC	PIN-TIA	AC	Back-Reflecting	No	\$12,225
F170A-DC	PIN-TIA	DC	Back-Reflecting	No	\$13,100
F171A-AC	APD-TIA	AC	Back-Reflecting	No	\$13,675
F171A-DC	APD-TIA	DC	Back-Reflecting	No	\$21,950
F172A-AC	PIN-TIA	AC	Non-Back-Reflecting	No	\$12,675
F172A-DC	PIN-TIA	DC	Non-Back-Reflecting	No	\$13,550
F173A-AC	APD-TIA	AC	Non-Back-Reflecting	No	\$14,100
F173A-DC	APD-TIA	DC	Non-Back-Reflecting	No	\$22,400
F175A-AC	PIN-TIA	AC	Back-Reflecting	Yes	\$13,875
F175A-DC	PIN-TIA	DC	Back-Reflecting	Yes	\$14,750
F176A-AC	APD-TIA	AC	Back-Reflecting	Yes	\$15,325
F176A-DC	APD-TIA	DC	Back-Reflecting	Yes	\$23,625
F177A-AC	PIN-TIA	AC	Non-Back-Reflecting	Yes	\$14,325
F177A-DC	PIN-TIA	DC	Non-Back-Reflecting	Yes	\$15,200
F178A-AC	APD-TIA	AC	Non-Back-Reflecting	Yes	\$15,750
F178A-DC	APD-TIA	DC	Non-Back-Reflecting	Yes	\$24,050

Standard delivery is 6 weeks. Pacing item is the receiver.

PDV Transceiver ModBlock Types

Model Number	Receiver Type	RF Output Coupling	Probe Type	Spotting Laser?	Price Each
F235A	PIN-TIA	AC	Back-Reflecting	Yes	\$19,475
F236A	PIN-TIA	DC	Back-Reflecting	Yes	\$20,350
F237A	PIN-TIA	AC	Non-Back-Reflecting	Yes	\$19,900
F238A	PIN-TIA	DC	Non-Back-Reflecting	Yes	\$20,775

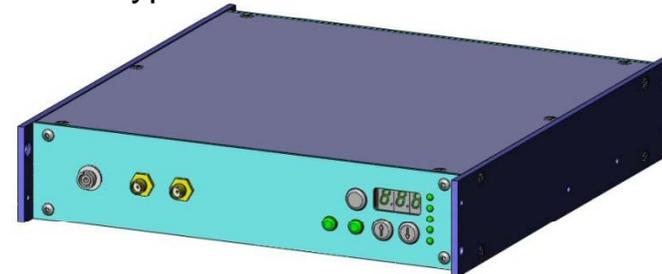
Standard delivery is 6 weeks. Pacing items are the laser and receiver.

With 20 mw 1550 nm laser, 40 m min. coherence length

Typical 1/4 rack receiver



Typical 1/2 rack transceiver



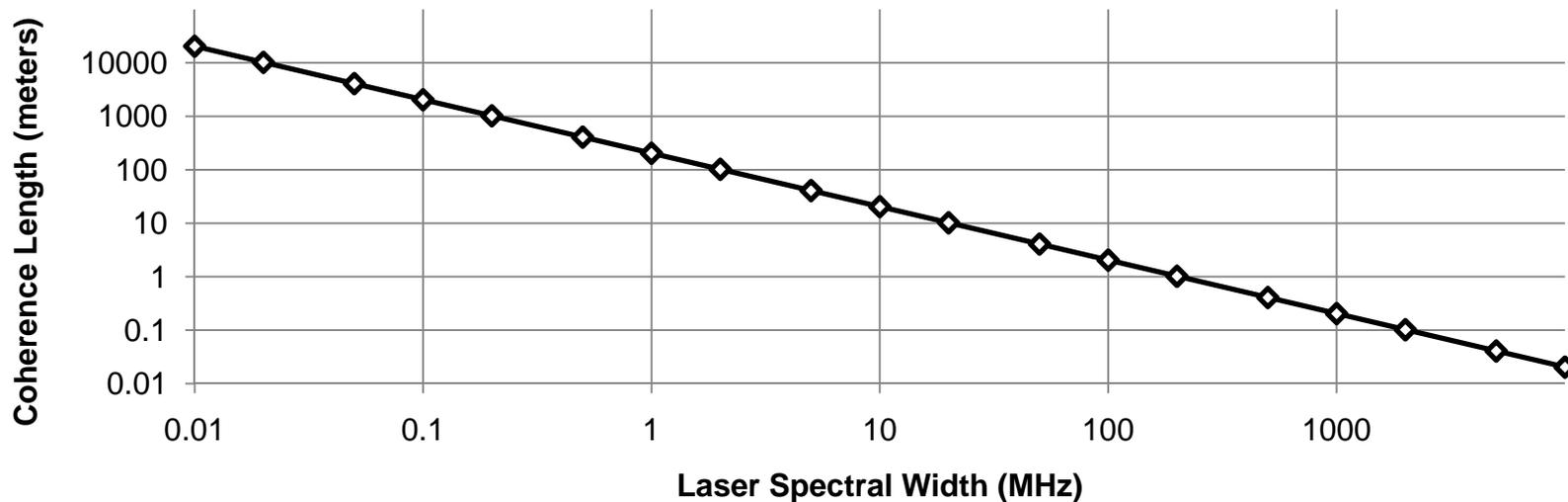
# Spotting Laser for PDV Systems

- Visible laser and low loss optical switch added between circulator and probe
- Provides visual diagnostic of probe light alignment to target before executing experimental run
- Adds moderate equipment cost and insertion loss
- Avoids improper experimental run setups

# Lasers and Coherence

- CW laser spectral bandwidth (BW) related to coherence length (L)
  - $L=c/(n*BW)$ ,  $c$ =speed of light,  $n$ =refractive index of fiber=1.4682 @ 1550 nm
- 1-20 mw 1550 nm communication lasers BW = 1 to 5 MHz typical
  - Low cost, low power, for 200-40 meter roundtrip PDV systems
  - Low cost tunable versions available in C-band
- 2 watt 1550 nm fiber ring lasers BW < 100 KHz typical
  - High cost, high power, for 2 km round trip PDV systems

## Coherence Length of 1550 nm Lasers in Singlemode SMF28 Fiber



# Optically Amplified Laser Sources

- Few commercial CW laser choices between 20 mw and 2 watts
  - Circulators rated 500 mw maximum
- Optical amplifier can be used to boost coherent laser power
  - Low cost communication laser can be used
  - Optical amplifier maintains coherency
  - Single wavelength optical amplifiers used
  - Output power outputs in the 100 mw (low cost) to 1 watt range

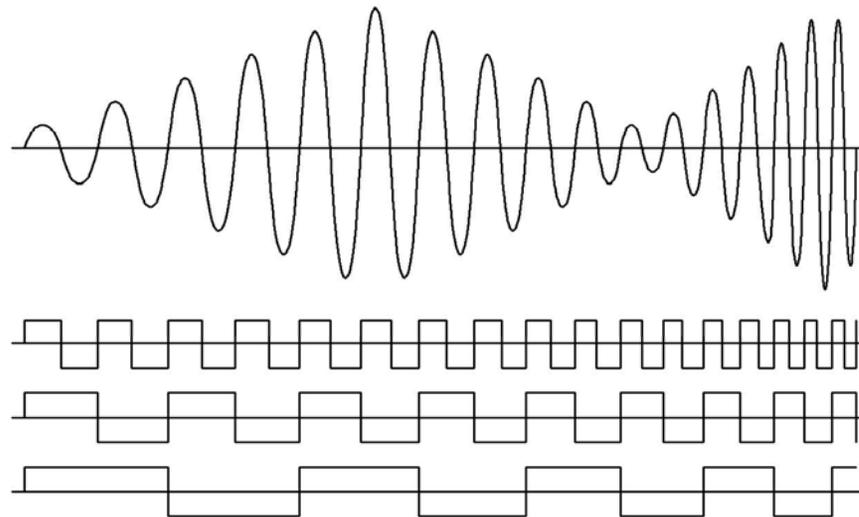
# Interferometry approximation for PDV

- Interferometer is fundamentally position based
  - Reinforcement or cancellation interference occurs in wavelength increments (1.55  $\mu\text{m}$ )
- PDV interferometer used to measure velocity, not position
  - 1.29 GHz per km/sec is rate of reinforcements and cancellations at receiver output
  - 645 MHz per km/sec is rate of reinforcements or cancellations at receiver output
  - Velocity information is provided by frequency, not amplitude
  - Position resolution several orders of magnitude better than what is needed for velocity
- Final velocity profiles from post-processing software are inherently grainy
  - Velocity profiles typically plotted on a linear scale with no better than 0.1% resolution
  - 0.1% resolution of 10 km/s full scale is 10 m/s resolution
  - 10 m/s is a 6.45 MHz rate of reinforcements or cancellations
- This means that the receiver output rate could be divided down
  - No perceptible resolution loss on the final velocity profile
  - Real time oscilloscope bandwidth could be reduced
  - Special fast counter circuit can be used to directly generate velocity profile
- Nice research and simulation science project for someone
  - Show divider modulus versus velocity profile resolution loss and target maximum speed

# Limiting Amplifiers and Frequency Dividers

- Special microwave amplifiers can remove amplitude variations from receiver output over a wide range (1000:1)
  - Eases post-processing software tasks
- Microwave divider can range amplifier output to lower frequencies
  - Negligible loss in velocity profile resolution
  - Lower oscilloscope BW and cost
  - Can provide oscilloscope trigger

Example analog  
(variable frequency and amplitude)  
and digital waveforms -  
receiver output,  
amp output,  
divide by 2 and 4 outputs



# Counter with DAC and/or RAM

- High speed circuitry with a special high speed counter, DAC output (for analog velocity profile) and/or RAM (for digital velocity profile)
  - Can replace real time oscilloscope and post-processing software
  - Can directly provide velocity profile outputs
- Microwave amplifier and divider can range into relatively low cost semiconductors
  - Divider not required for low velocity applications
  - Very high speed counter circuitry possible at higher cost to reduce divider modulus
- Counter output stored in RAM, then RAM and/or DAC read out
- Result scaled by divisor to recover original velocity profile

# Single Box PDV Systems

- A variety of single box PDV systems become possible
- All PDV items contained in one enclosure, except probe
- Can be customized to the application
- For 20 mw to 500 mw range
- Coherence lengths up to 200 meters, 40 meters best
- Direct velocity profile outputs, analog and/or digital
- Extendable to many channels
- Significantly lower cost than classical PDV systems

# Food for Thought

What could be measured with these commonly available telecom devices?

Temperature or chemical composition changes?

Better triggers? Channel tags? Multiple channels? Target direction?

- Optical modulators - DC to >10 GHz telecom optical amplitude and phase modulators
- Tunable lasers and filters
  - C-band telecom tunable lasers and filters
  - Fast tunable lasers (optical coherence tomography?)
  - Femto-second pulse lasers
- Fast tracking, wide range clock recovery circuits (aka phase locked loops)
  - Could be used instead of counter/DAC/RAM method for direct velocity profile readout
  - “Cook-off” oscilloscope triggers to reduce false triggering
- Optical time delays - Time multiplex multiple PDV channels to one oscilloscope
- Other - Electronic variable optical attenuators, fast optical switches (ns to ps ranges), WDM splitters and combiners with many laser colors, wavelength converters, FC/UPC connectors instead of FC/APC, fast optical scanners

# Conclusion

- PDV systems for NBR perform better than BR systems (factor of 2.7)
- Use AC coupled PIN receivers where possible, lowest cost, best availability
- Little technical advantage to using APD receivers, higher risk of overload damage
- Spotting laser is useful add-on to PDV system for diagnostics
- Optically amplified communication lasers can fill 20 mw to 1 watt availability gap
- Coherence length requirements below 200 meters allow lost cost laser use
- Interferometry resolution overkill for PDV velocity measurements
- Special amplifiers after receiver can make post-processing easier
- Frequency dividers after receiver can reduce oscilloscope requirements and costs
- High speed counter circuitry with DAC and/or RAM
  - Can replace real time oscilloscopes and post-processing software
  - Can provide direct analog and/or digital velocity profile outputs
- Many other telecom devices might be usable for PDV material science research



# Third Millennium Engineering

*Helping customers create and manufacture  
advanced technology products for our future*

Can supply any PDV system or equipment required or shown in this paper

- Supplier of high quality custom engineered equipment, products, and systems using fiber optic, microwave, RF, or advanced technologies
- Quantities from 1 to 10+ units in typically 2-3 months
- Simple to complex, typically multi-functional, provided with any features and accessories needed
- Formal specifications not required, verbal specifications and goals adequate to produce quote
- Consulting, Engineering, Manufacturing, Support
- Commercial, Industrial, Defense, Emerging Industries
  
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- Plano Texas, since 1996, registered Texas engineer, 3CPK6 cage code
- View PDV and other catalogs on website, call or email to receive quote

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