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Fiber Laser Coherent LIDAR for Wake-Vortex Hazard Detection

M. Akbulut, J. Hwang, F. Kimpel, S. Gupta, H. Verdun

Fibertek Inc. , Herndon VA

This work is funded by NASA Langley Research Center

Image from www.aviationexplorer.com

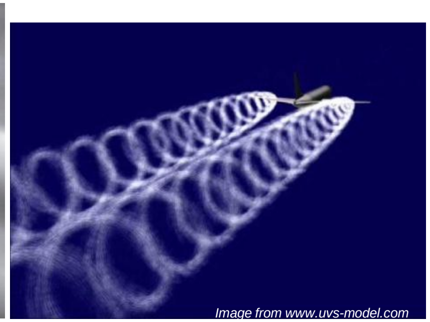

Image from www.uvs-model.com

Image from www.tc.gc.ca

Image from www.wikipedia.org

Introduction


Image from www.tc.gc.ca

Applications for airborne Coherent Lidar

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- Aircrafts are flying "blind" with respect to atmospheric hazards
  - Wake-vortices
  - Turbulence
  - Air drafts
  - Wind-shear , etc.

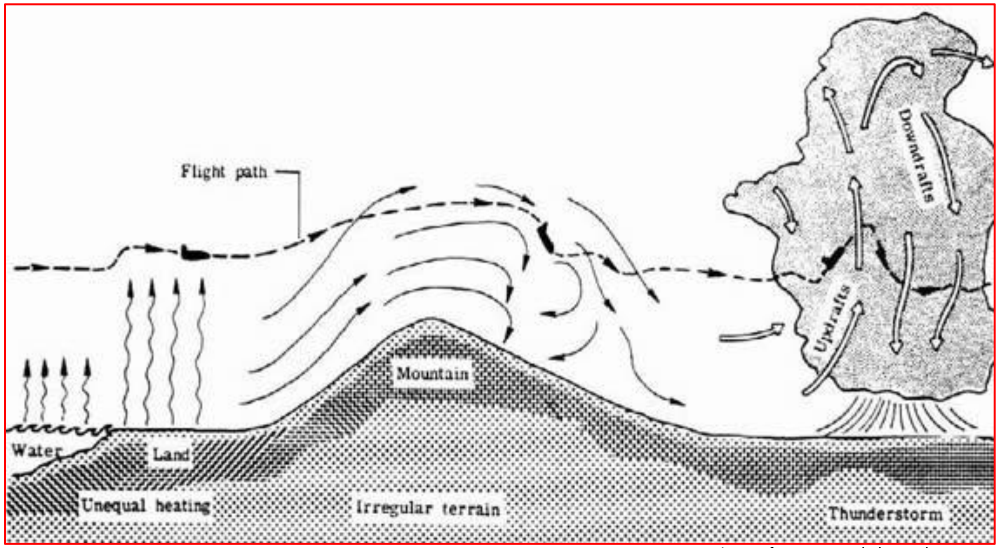

Image from www.aviationexplorer.com

- Airborne laser radar sensors can be useful for:
  - Atmospheric hazard detection
  - Flight pattern and Airport traffic optimization

  (Reduced fuel consumption , optimized spacing)

Wake-Vortices at airports

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NBC WASHINGTON

HOME > NEWS > LOCAL

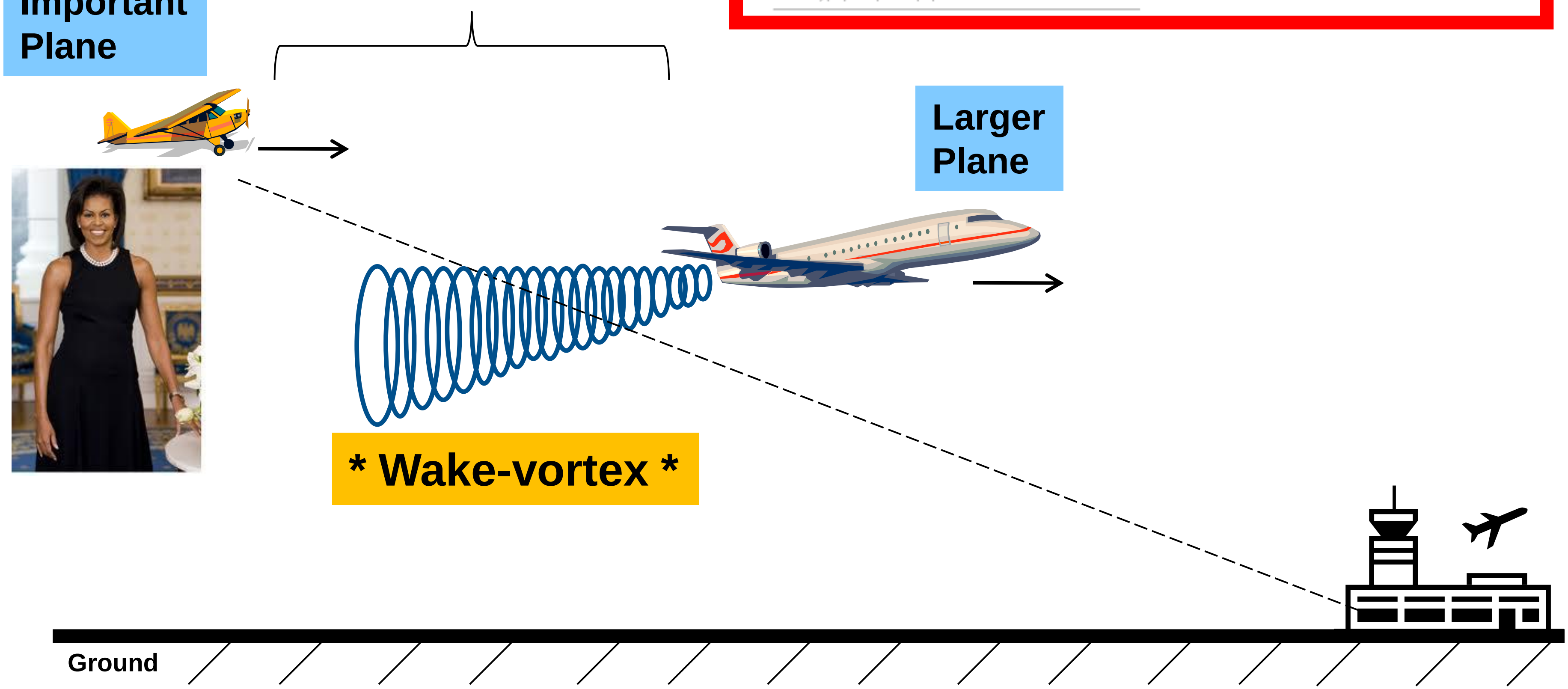
First Lady's Plane Gets Too Close to Cargo Jet

Air traffic controller mistake may be to blame

Tuesday, Apr 19, 2011 | Updated 11:28 PM EDT

Very Important Plane

Minimum 5 mile separation



Coherent LIDAR theory

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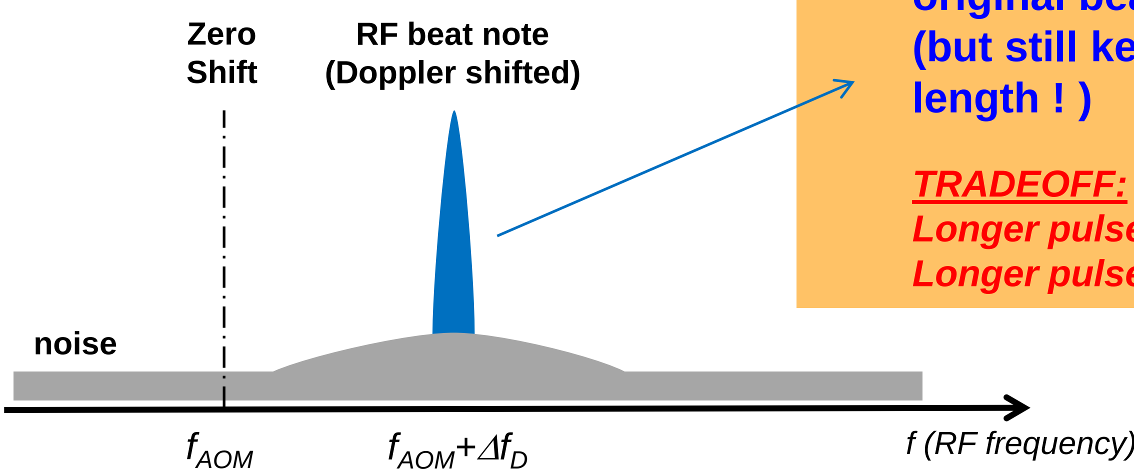
- Doppler frequency shift is proportional to <u>line-of-sight wind vector</u>

  for 1.55 μm , $$\Delta f_{DOPPLER}(MHz) \cong 1.29 \times V_{WIND}(m/s)$$

- Noise and Broadening on the coherent RF beat note
  - Original optical linewidth , <u>Pulsing of the laser Tx</u> , Laser AM and PM noise
  - Photodetection noise (<u>shot</u>, thermal, etc.)
  - RF timing and amplifier noise , sampling/digitizing/windowing noise
  - Atmospheric effects



800 ns pulse broadens ~4 kHz original beat note to ~1.3 MHz (but still keeps original coherence length !)

<u>TRADEOFF:</u>
Longer pulse - smaller linewidth
Longer pulse - worse spatial resolution

Challenges for airborne Wake-Vortex LIDAR

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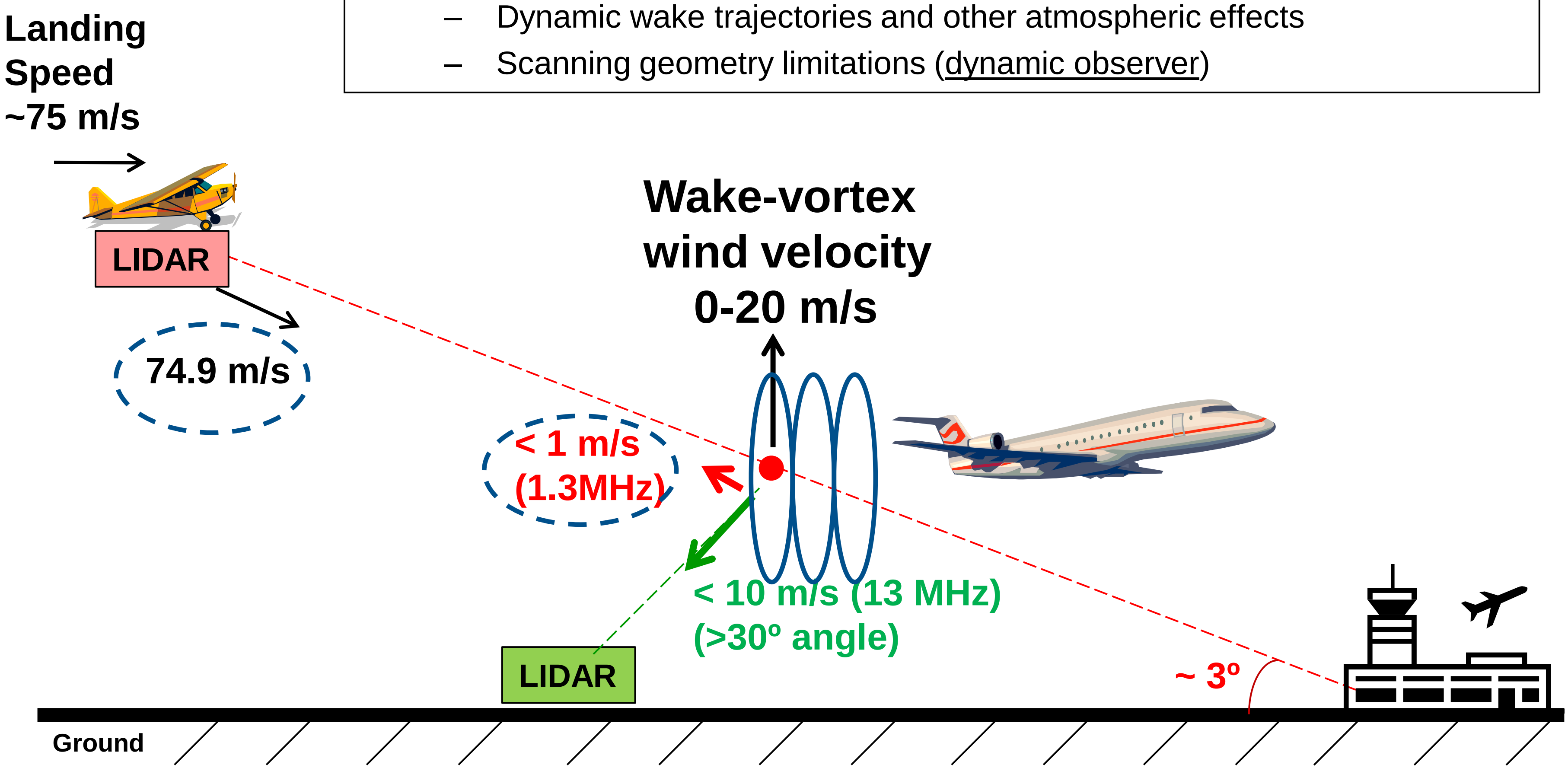
- Forward-looking airborne wake-vortex measurement
  - Axial line-of-sight reduces dynamic range (Need very fine resolution)
  - Need accurate measurement of platform speed, attitude, etc.
  - SWaP and Cost limitations (multi-function instrument ?)
  - Dynamic wake trajectories and other atmospheric effects
  - Scanning geometry limitations (dynamic observer)



Coherent Lidar Transceiver Development

Coherent LIDAR system level details

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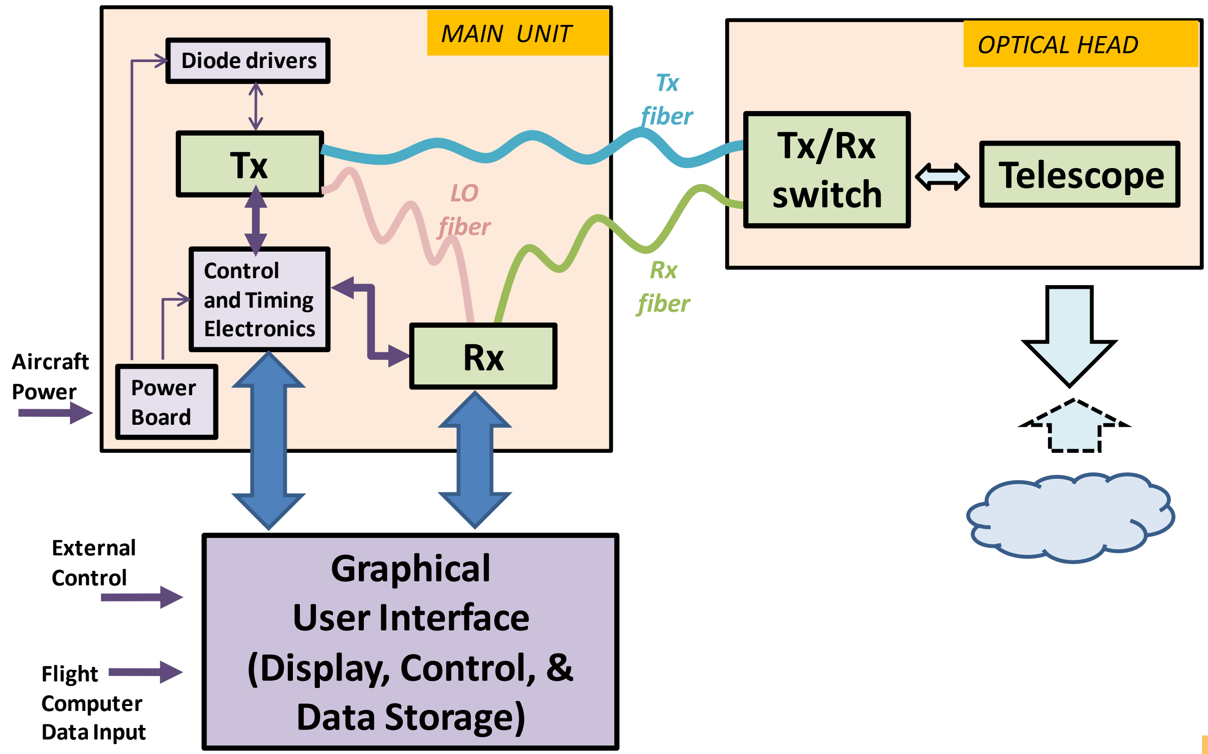
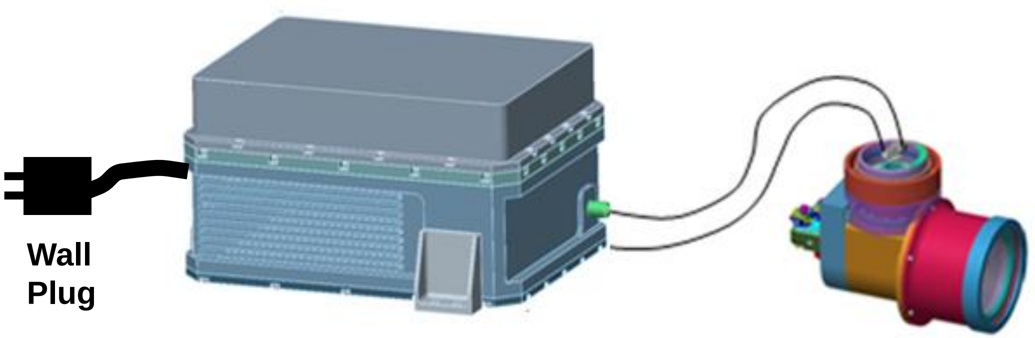


- Eye-safe, all-fiber 1550 nm
- Two-piece design
  1. Main unit:
     - Includes Tx, Rx, and all electronics
  2. Optical head
     - Includes Tx/Rx switch, telescope
- Forced-air cooling



SWaP goals

Main unit: < 12”x10”x7”
< 30 lbs
Total: < 600 W power

LIDAR performance simulations

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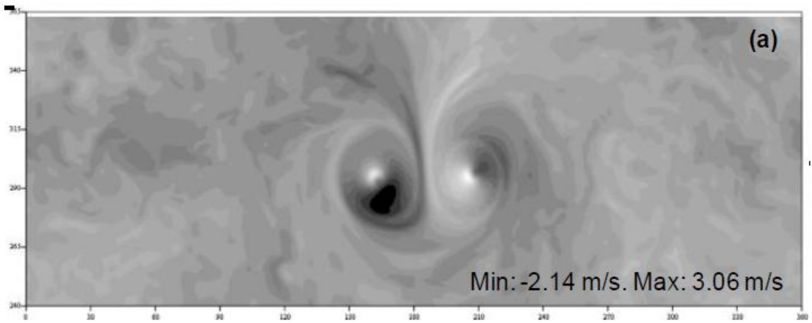
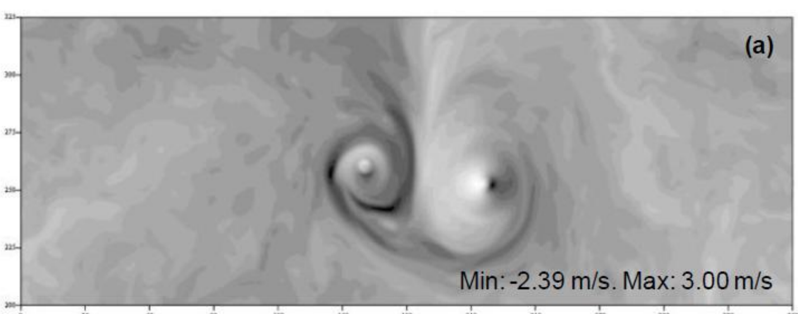
- TASS data for a Boeing-747 landing supplied by NASA

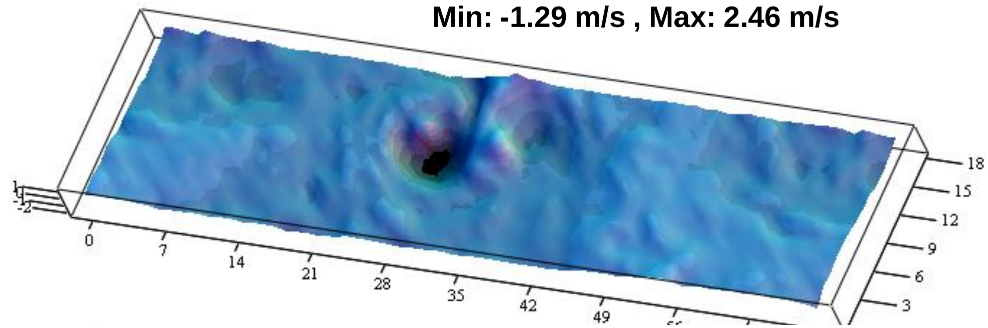
TASS Data
(<1.25m x-y resolution)

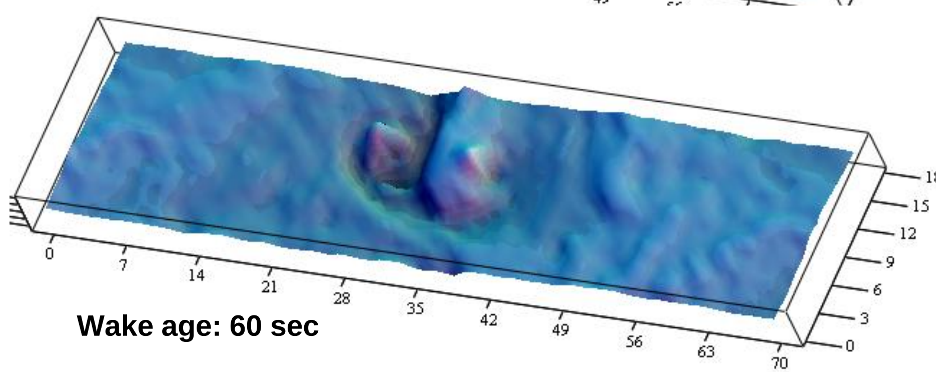




Fibertek LIDAR
Scan simulations
(<7m x-y resolution)

Wake age: 24 sec
Min: -1.29 m/s , Max: 2.46 m/s





Wake age: 60 sec

Min: -2.09 m/s , Max: 2.61 m/s

Range versus energy estimation

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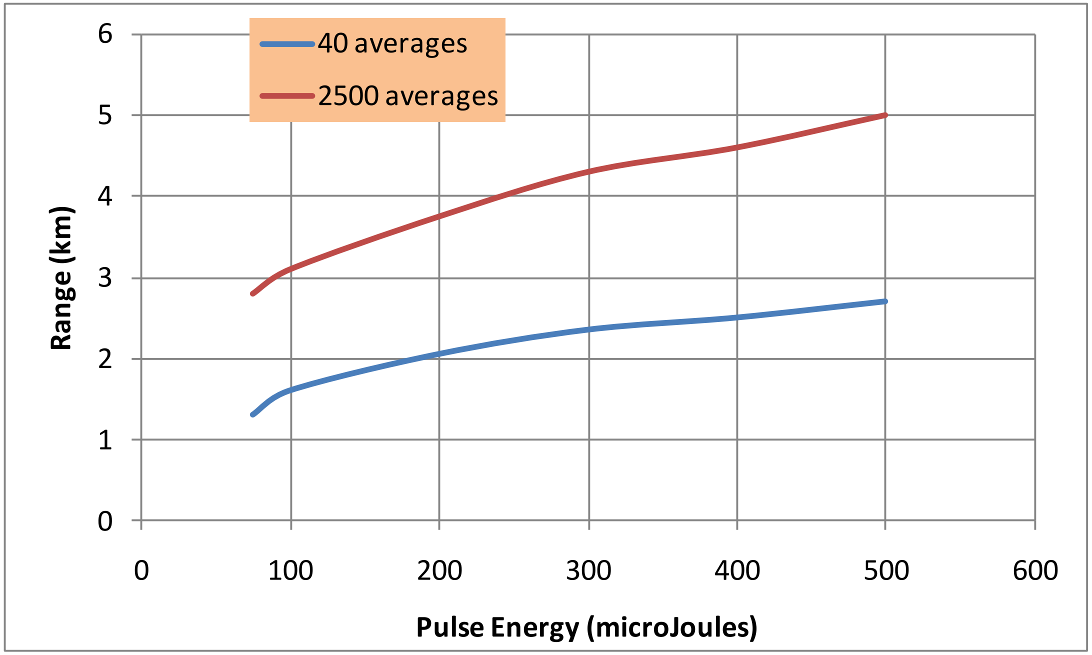
- 25 kHz rep. rate
- 5cm Rx aperture
- Final SNR=6

- **40 averages** (>600 Hz data)
  - 120µJ , ~1.7 km
  - 500µJ , ~2.7 km

- **2500 averages** (10 Hz data)
  - 120µJ , ~3.2 km
  - 500µJ , ~5 km



Fiber-Optic Lidar Transmitter (Tx)
Performance limitations

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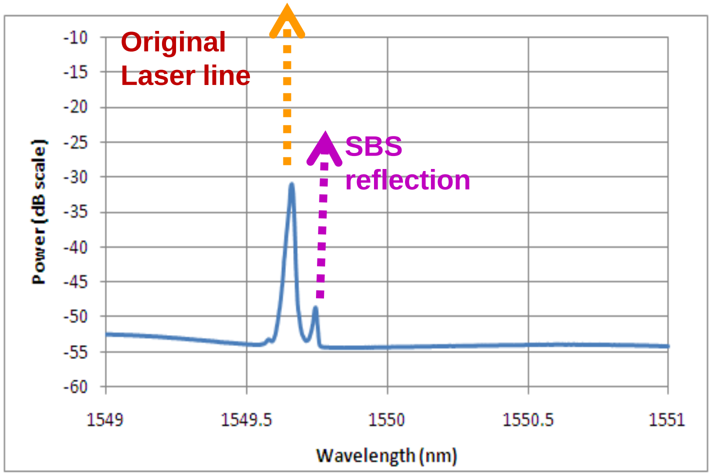
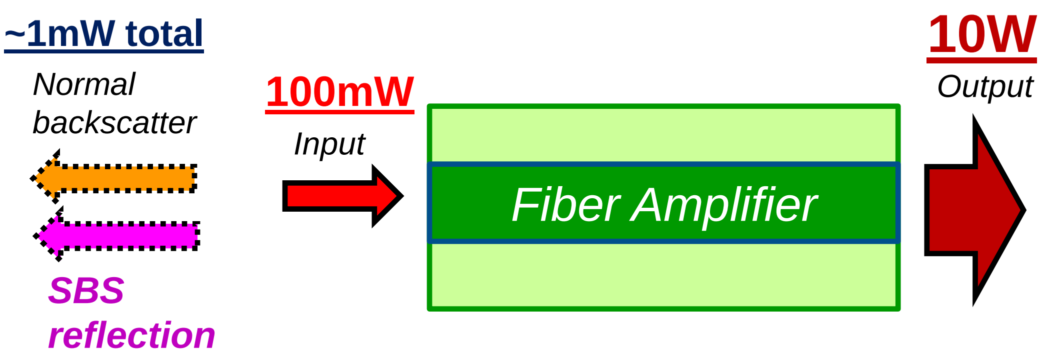
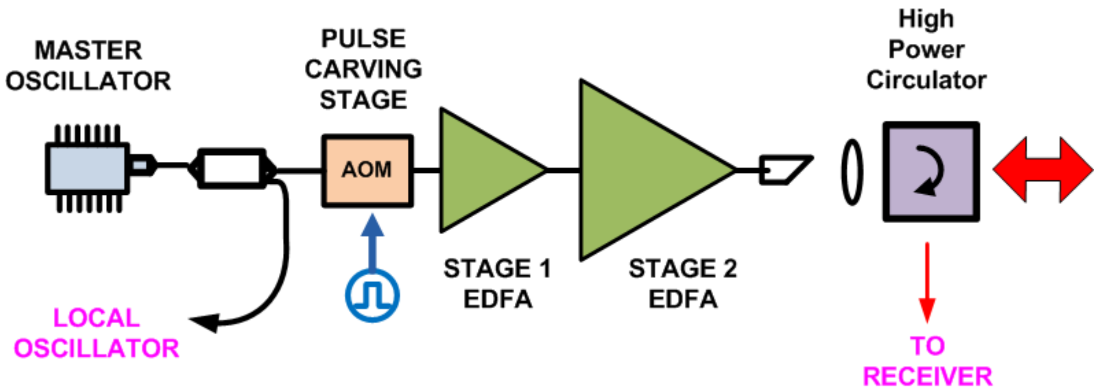
- Fiber lasers optimal for
  - High average power, High repetition rate, Narrow linewidth, Flexible operation, Data modulation capabilities, Wall-plug efficiency, SWaP metrics, Production cost and repeatability
- Fiber lasers not optimal for
  - High energy (~mJ single mode), high peak power (~MW short pulse)
- Stimulated Brillouin Scattering (SBS) is the main energy-limiting factor for long pulses (800ns in this case)
  - Energy goes backward stealing gain and causing catastrophic damage
  - SBS threshold ≡ Equal peak levels backward (≤ 35 dB below forward)





Lidar Tx - Design



- Eye-safe 1550 nm wavelength
- Master Oscillator Power Amplifier (MOPA) Architecture
  - Ultra-low noise Master Oscillator
- Acousto Optic Modulator (AOM) for pulsing
  - High extinction ratio Pulse Carving
  - Optical frequency shifting of TR/REC with respect to LO
- All PM Erbium-doped fibers for amplification
  - Multi-stage MOPA for lowest noise with highest gain
  - Increasing MFD at each stage, COTS LMA fibers
- *Proprietary techniques for SBS mitigation*

Lidar Tx – Master Oscillator

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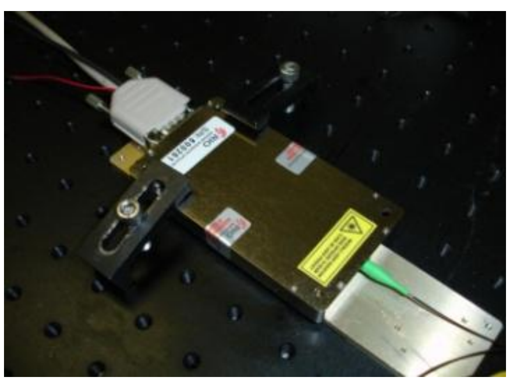
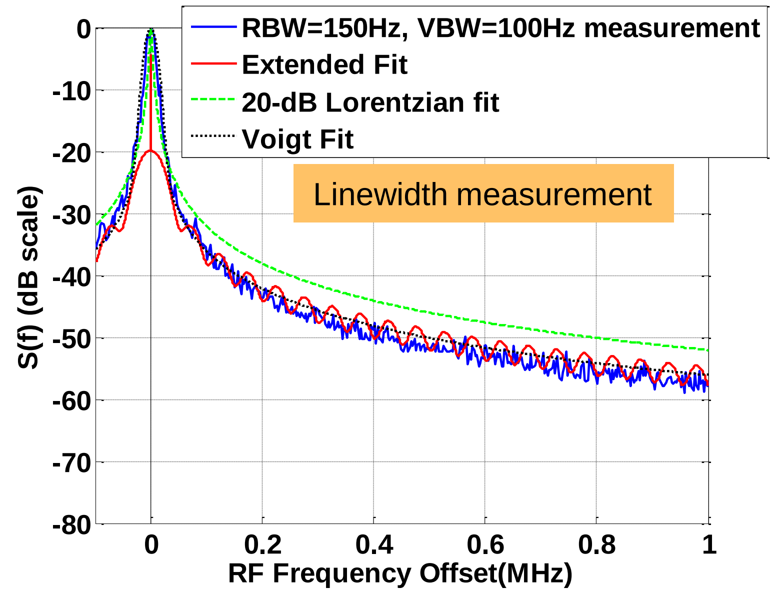
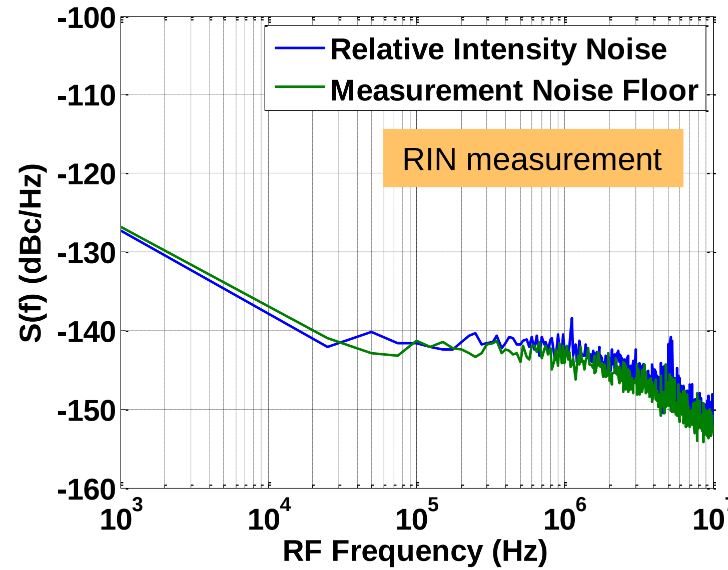
- Ultra-low noise 1550nm master oscillator (RIO Inc.):
  - Semiconductor + PLC based
  - ~2.5 kHz linewidth
  - -140 dBc/Hz RIN noise
  - SWaP efficient
- Pulsed with external AOM at 25 kHz, 800 ns pulse width

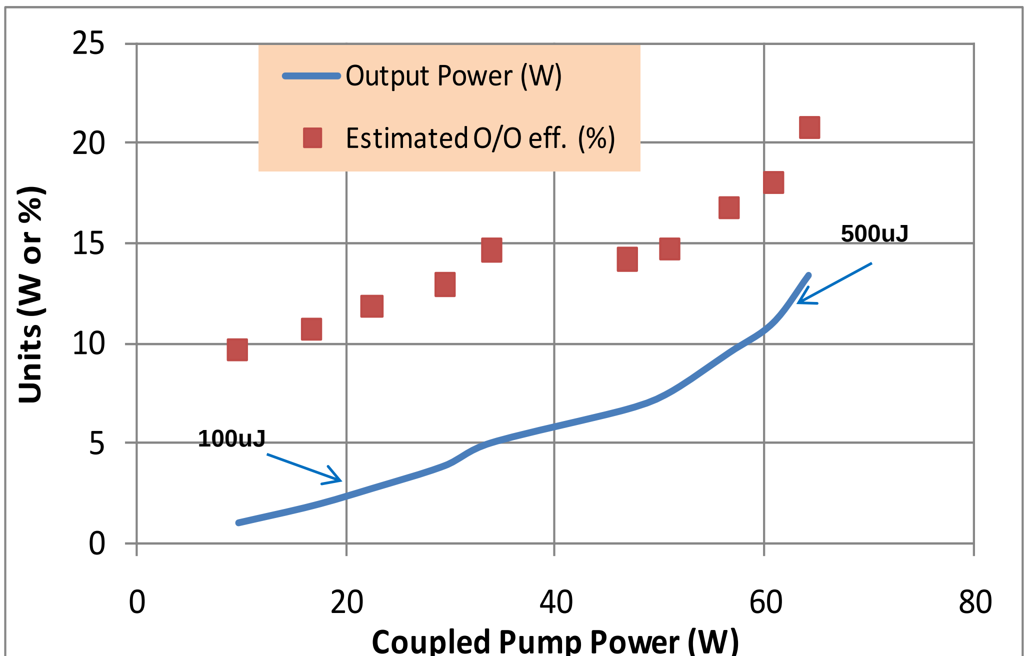


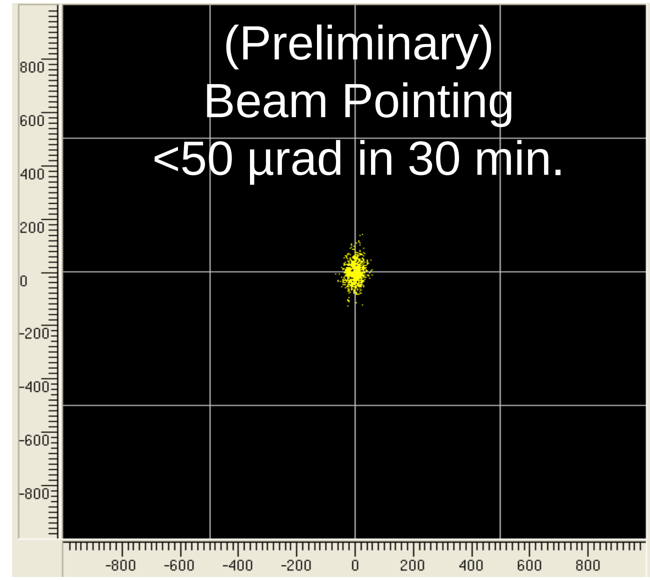


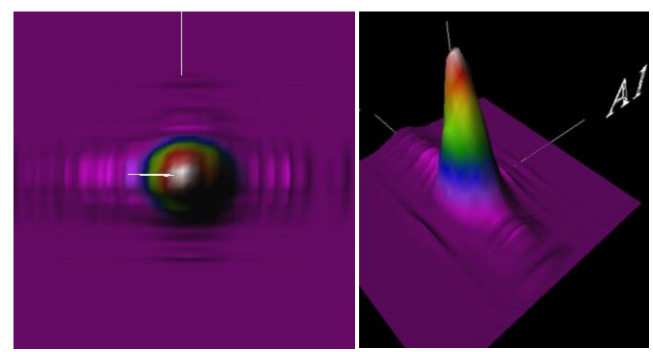


Lidar Tx – Power Amplifier

- PM LMA commercial Er-doped fiber
- Up to ~65 W coupled pump
- Up to ~14 W output power (~21% eff.)
- ~17 dB PER measured
- Single Mode ($M^2 < 1.2$) , stable pointing (even with bare fiber tip and standard optic mounts)







"Standard" SBS mitigation strategies

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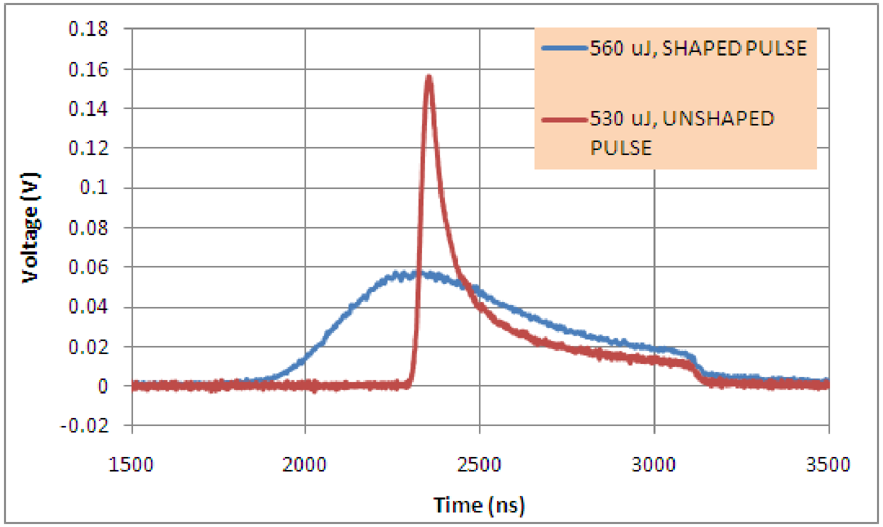
1. Input SBS threshold and output power depends on GAIN
   - Increase Gain to increase SBS threshold
   - TRADEOFF: Too much gain causes parasitic lasing

$$Input\ SBS\ Threshold = CONSTANT \times \ln(GAIN)$$

2. Pulse steepening due to very long pulses
   - Reduces SBS threshold and LIDAR resolution
   - Pre-emphasis shaped pulse instead of rectangular shape (non-optimized)



3. Other techniques
   - Counter-pumping (reduces L_{eff})
   - SBS-mitigated fibers (acoustic-tailored, temperature-tuned, segmented, etc.)
   - Specialty VLMA fibers (photonic-crystal, multi-core, leaky channel, HOM, highly doped, etc.)

Tx output with "standard" SBS mitigation
Gain optimization and Pulse Shaping

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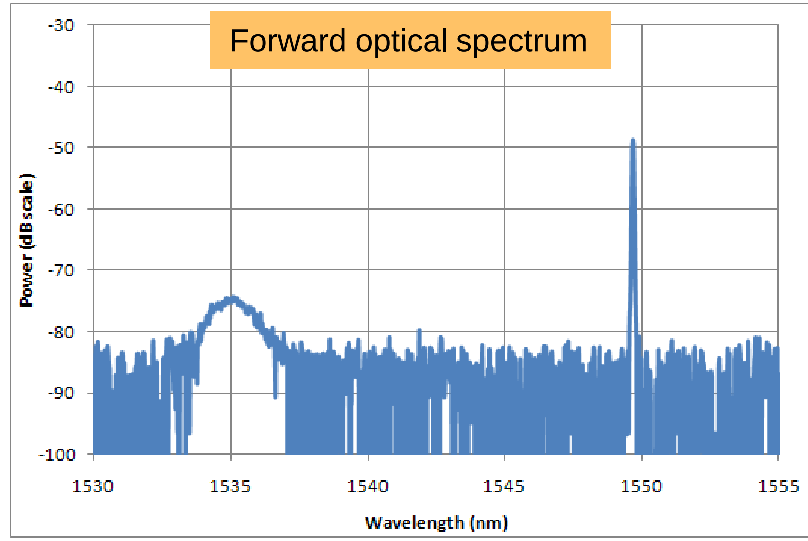
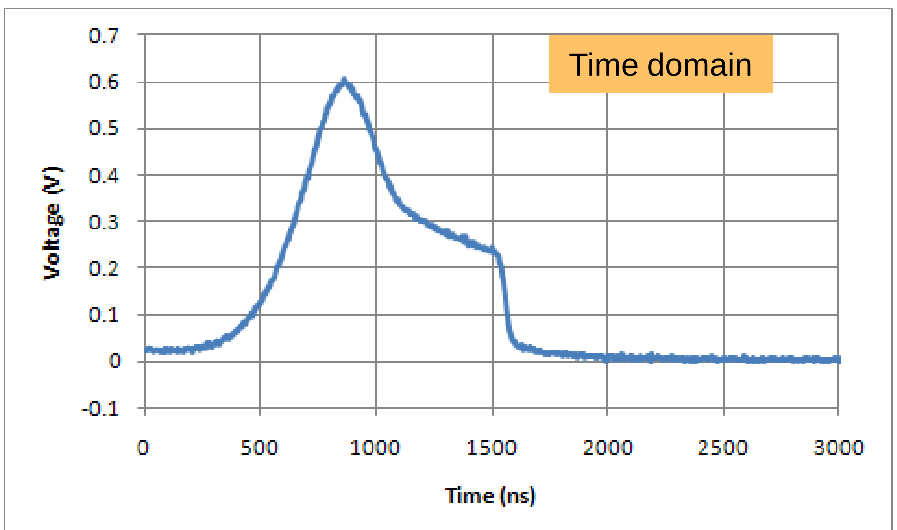
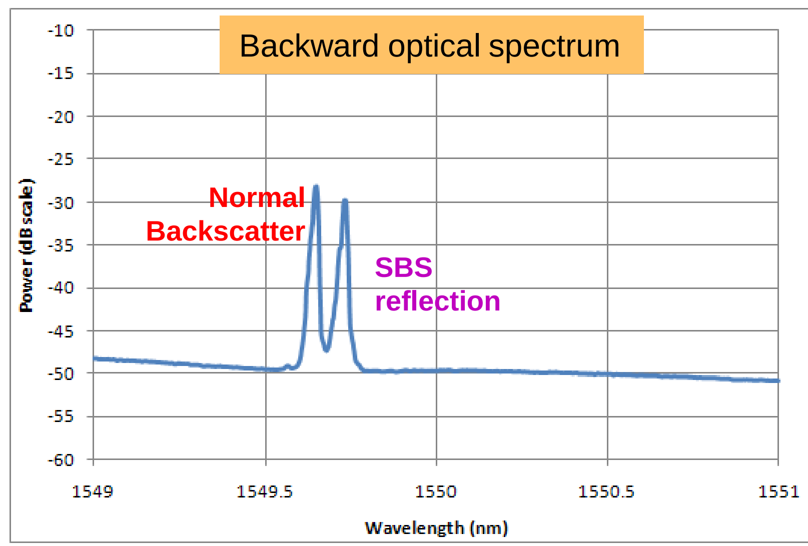
- Increased gain in amplifiers while controlling ASE levels
- Implemented pre-emphasis pulse shaping (non-optimized)

120 μJ @ 25kHz
220 μJ @ 10kHz
at SBS threshold and low ASE







Tx output with “advanced” SBS mitigation

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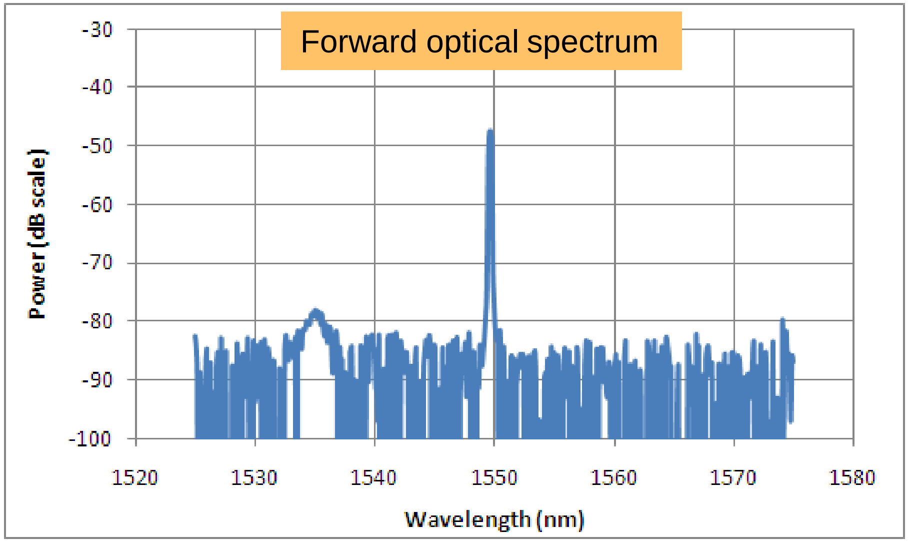
- Proprietary Fibertek techniques
- SBS threshold increase beyond standard methods

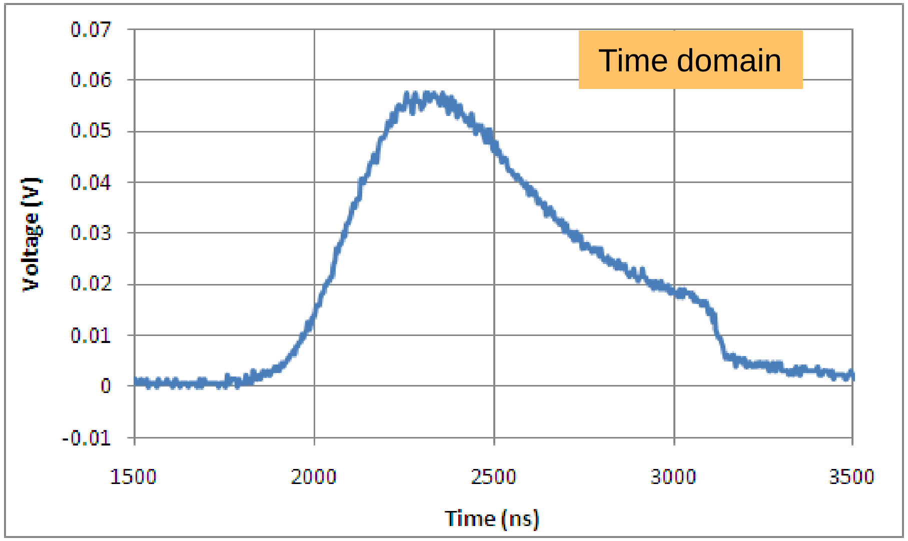
560 μJ @ 25kHz

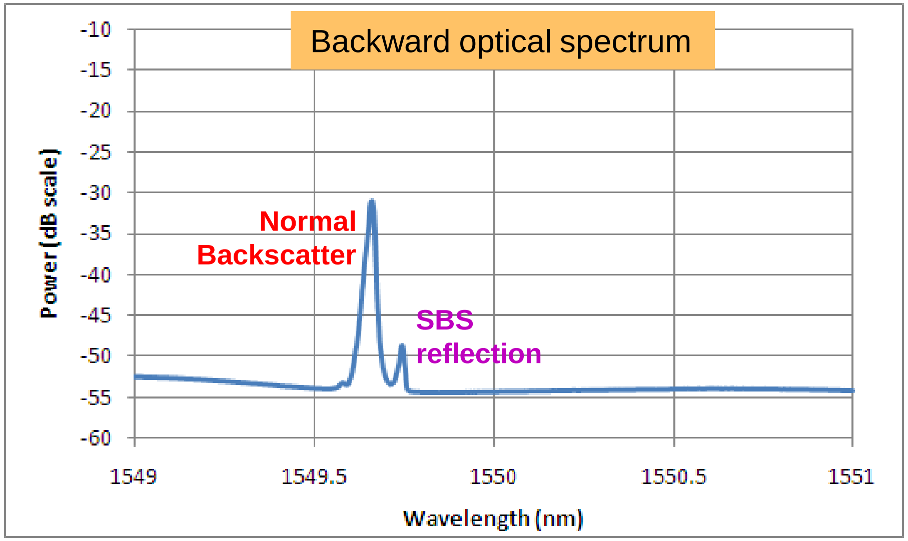
800 μJ @ 10kHz

(pump limited)

with minimal SBS and ASE







Survey and simple comparison

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- LIDAR performance figure-of-merit (FOM) for fixed Rx aperture:

$$FOM = ENERGY \times \sqrt{PRF}$$

	LIDAR Vendor-Model	Energy (mJ)	PRF (Hz)	FOM
Solid State	LM-CTI WindTracer	2	500	45
	LM-CTI WindTracerX	5	500	112
	NASA-LaRC DAWN	250	10	790
Erbium fiber	Onera-Leosphere	0.12	12000	13
	ENRI-Mitsubishi	0.2	4000	13
	Fibertek 120 µJ standard	0.12	25000	19
	Fibertek 220 µJ standard	0.22	10000	22
	Fibertek 560 µJ advanced	0.56	25000	88
	Fibertek 800 µJ advanced	0.80	10000	80

Receiver (Rx) Design

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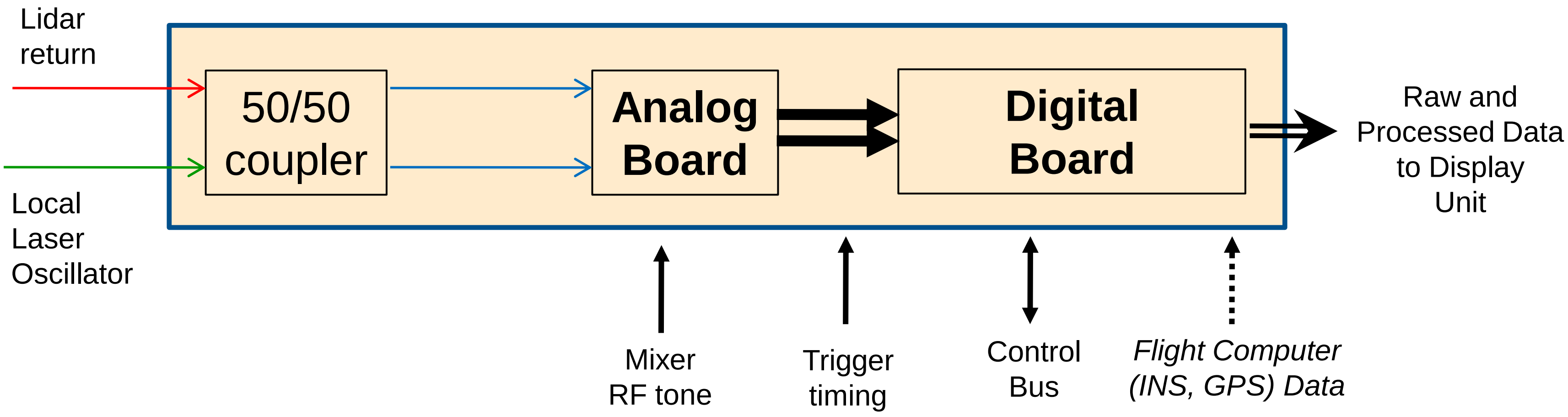


- Receiver is comprised of two parts:
  - Analog board (Coherent, balanced photodetection, Platform velocity correction)
  - Digital board (Gs/s sampling , Real-time DSP and curve-fitting, I/Q, Gb/s data interface)

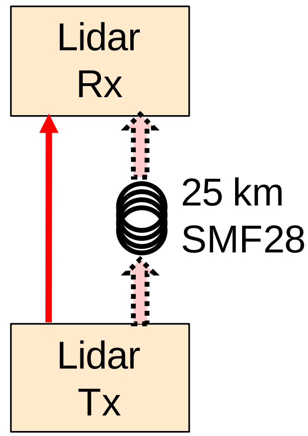
- Analog board sensitivity of **~ 2 fW** (SNR=6)
- Wind velocity measurement range of **± 20 m/s** with **~0.1 m/s** resolution
  - Airborne platform velocity correction of ~20 – 200 m/s (data read from external GPS)
- **~40-120m** range slice resolution
- <3.5 sec. data refresh rate (40 pulse avg., ~2000 pixels for certain scanning geometries)

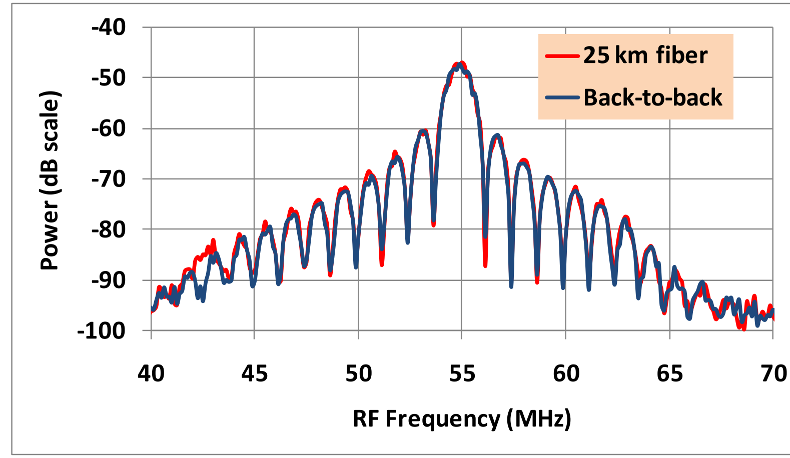
Preliminary Lidar Testing

Lidar Tx + Rx – Preliminary lab experiments

1. Compare back-to-back and 25 km of SMF28 delay
   - ~18.5 km range in air
   - ~1µW received power (40 pJ)
   - Zero Doppler shift=55 MHz

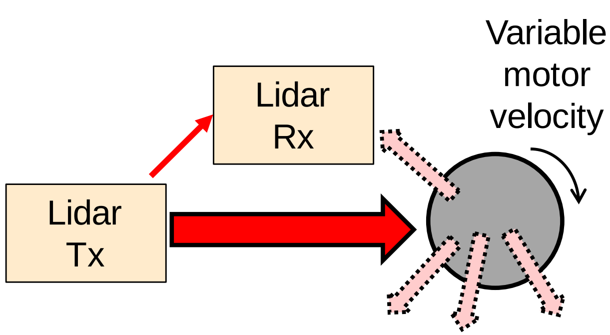
✓ Coherence Length

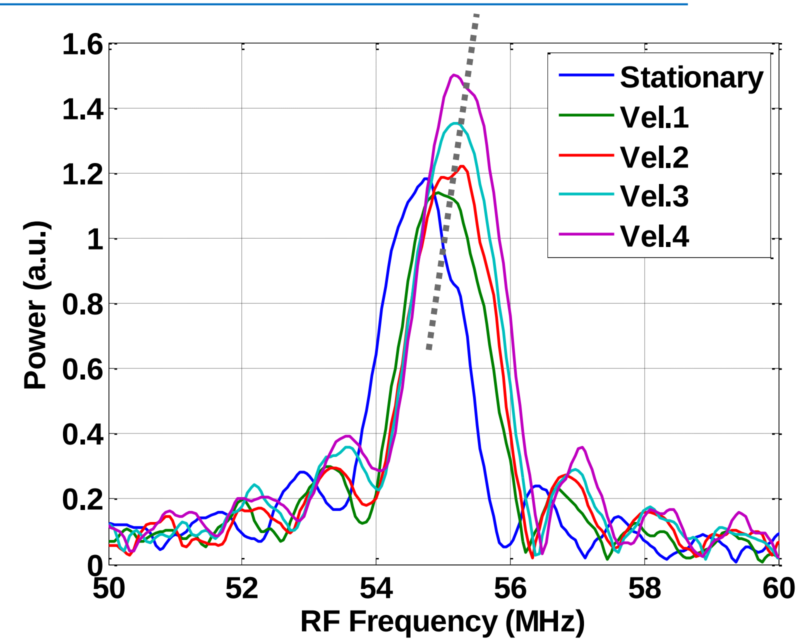




2. Test with variable target velocity and partially-completed receiver
   - ~0.1 MHz (< 0.1 m/s) resolution
   - ~100 pW received power (4 fJ)

✓ Sensitivity
✓ Resolution





Conclusions

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- We present a fiber-optic, eye-safe Coherent LIDAR transceiver
  - 560µJ of energy at 25 kHz rate, 800µJ@10kHz (pump limited)
  - 800 ns pulsewidth with <3kHz local oscillator optical linewidth
  - ~2 fW estimated receiver sensitivity with >2 km range
  - Velocity measurement of ± 20 m/s with ~0.1 m/s resolution
  - Desirable SWAP metrics for airborne platform

- We believe that this lidar can be a useful tool for airborne wind sensing, turbulence and wake-vortex detection