



# Fiber-based Doppler Lidar for Vector Velocity and Altitude Measurements

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Frontier in Optics and Laser Science

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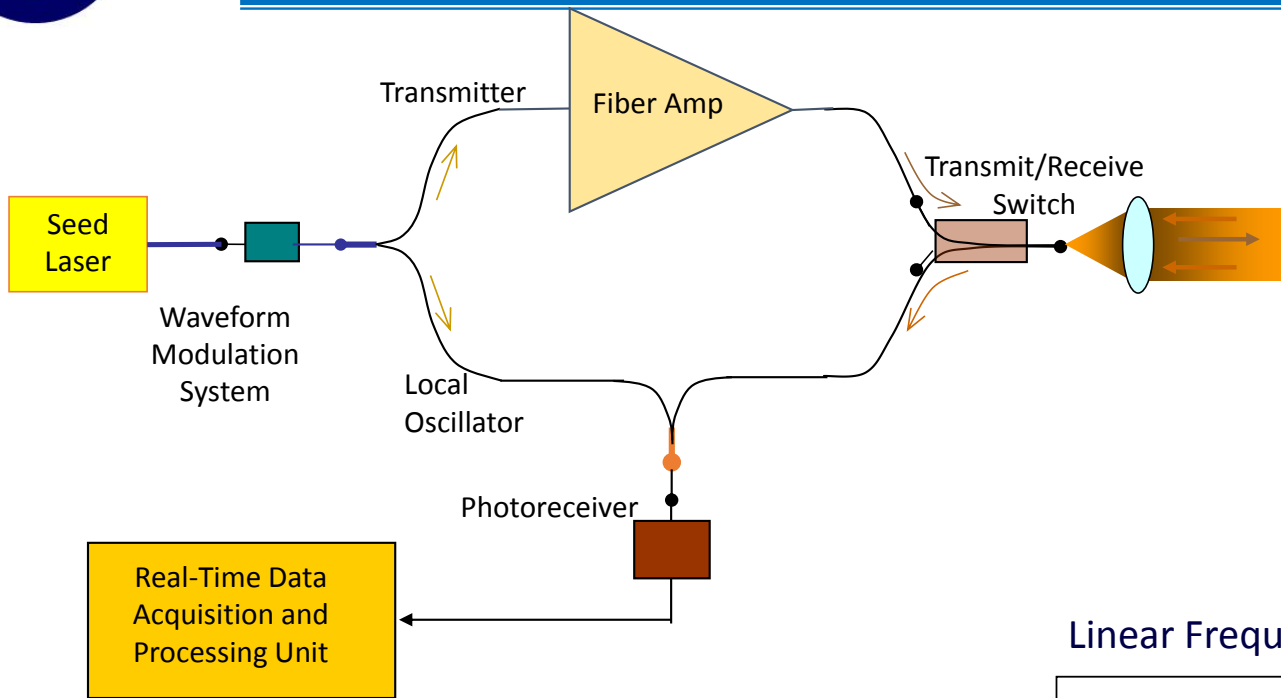


# Navigation Doppler Lidar (NDL)

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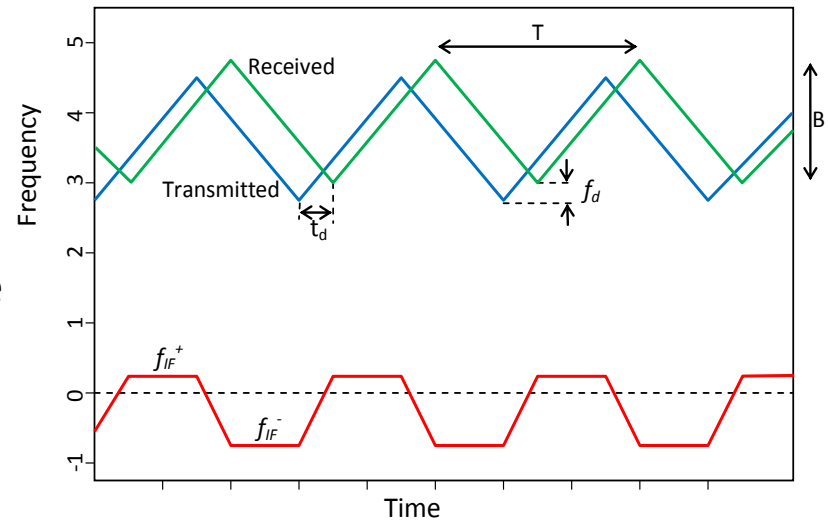


- Conventional terrestrial navigation relies on GPS for determination of vehicle position and velocity
- GPS-deprived environment of space requires onboard sensors (past landing missions used radars)
- NDL provides necessary data for “precision navigation” and “gentle touchdown” for future landing missions:
  - Vector Velocity
  - Ground Altitude
  - Ground-relative Attitude
- NDL offers an order of magnitude higher precision than microwave radars and much higher data quality (low false alarms) while reducing required size, mass, and power

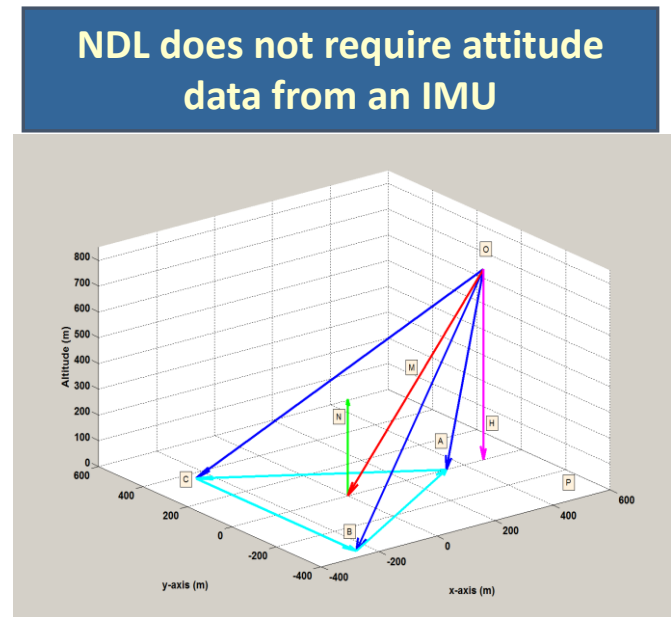
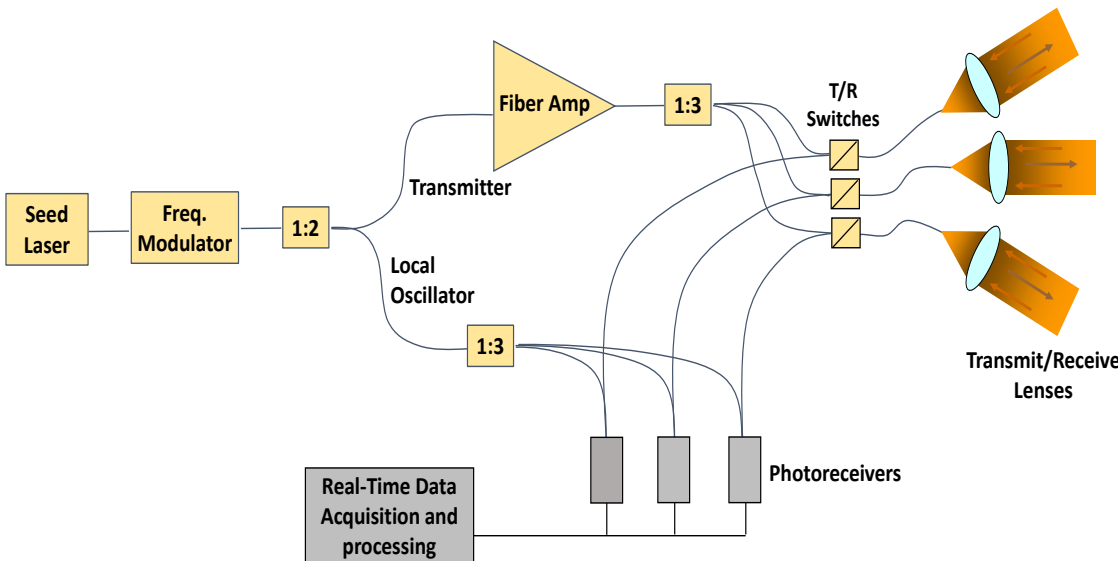


- Utilizes Doppler shift of scattered continuous-wave laser beam to measure velocity along the laser beam
- Application of a waveform modulation allows measuring range to ground

## Linear Frequency Modulation Technique



- NDL Measures velocity and range along three different laser beams
- Simultaneous line-of-sight measurements are used to determine:
  - Velocity Vector ( $V$ )
  - Altitude relative to local ground
  - Surface-relative Attitude



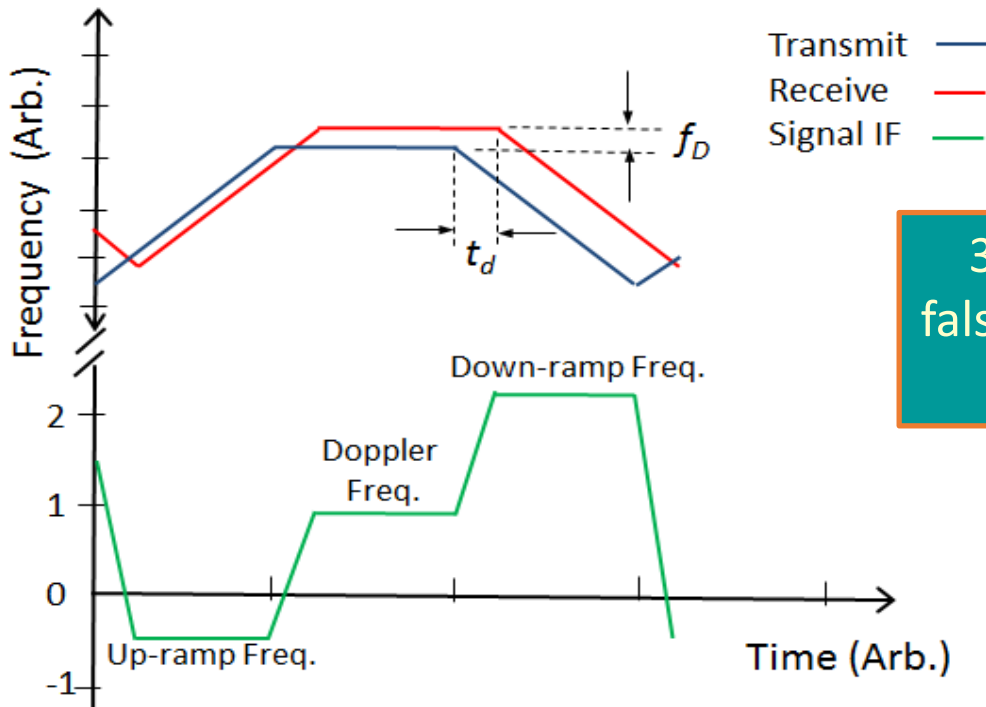
# NDL prototype used for ALHAT tests

- Fully-autonomous operation
- Integrated real-time processors
- Subjected to thermal and vibration tests
- Helicopter and closed-loop Morpheus flight tests as an integrated sensor of the GN&C system



- All the lidar components are housed in the electronic chassis.
- Optical head consists of three transmit/receive lenses connected to the chassis via a long armored fiber optic cable.
- Optical head mounts rigidly to the body of the vehicle with a clear view of the ground while the electronic chassis may be installed anywhere on the vehicle.

# Frequency Modulated, Continuous Wave (FMCW) Waveform

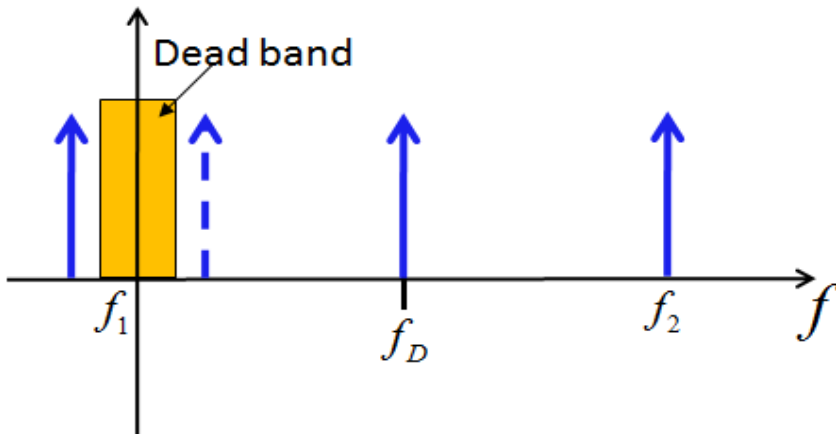


3 segments waveform minimizes false alarms due to zero-crossing and signal ambiguity

$$V = \frac{f_D \cdot \lambda}{2}$$

$$R = \left( \frac{TC}{2B} \right) \left( \frac{f_{IF}^+ - f_{IF}^-}{2} \right)$$

$$V = \left( \frac{\lambda}{2} \right) \left( \frac{f_{IF}^+ + f_{IF}^-}{2} \right)$$





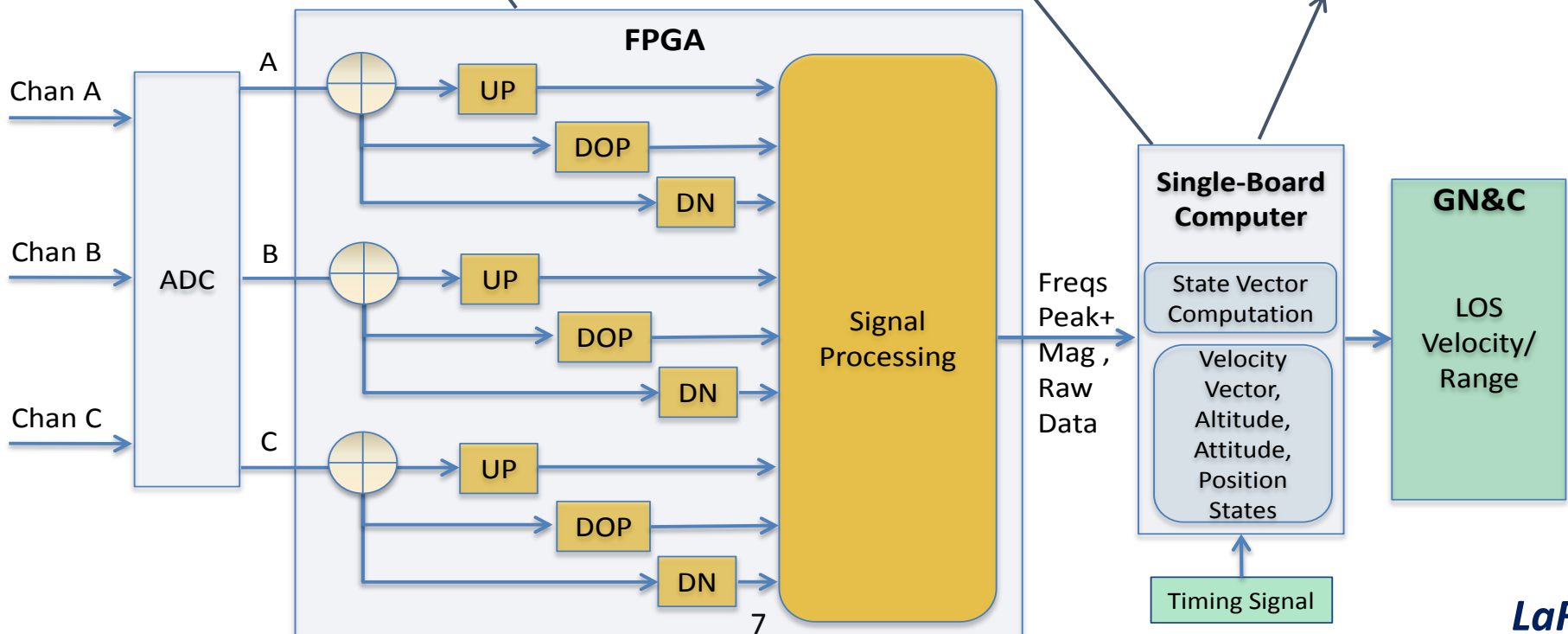
# Doppler Lidar Real-Time Processor and System Controller



- High resolution FFT (9 X 64k points)
- Filtering, peak detection, frequency ambiguity removal algorithms
- Processing time < 33 ms

- Compute LOS Velocity and Range
- Compute Vector Velocity, Altitude, Attitude

- Initialize and monitor subsystems, and generate timing signals
- Configure FPGA
- Receive commands, and timestamp and send output data to vehicle



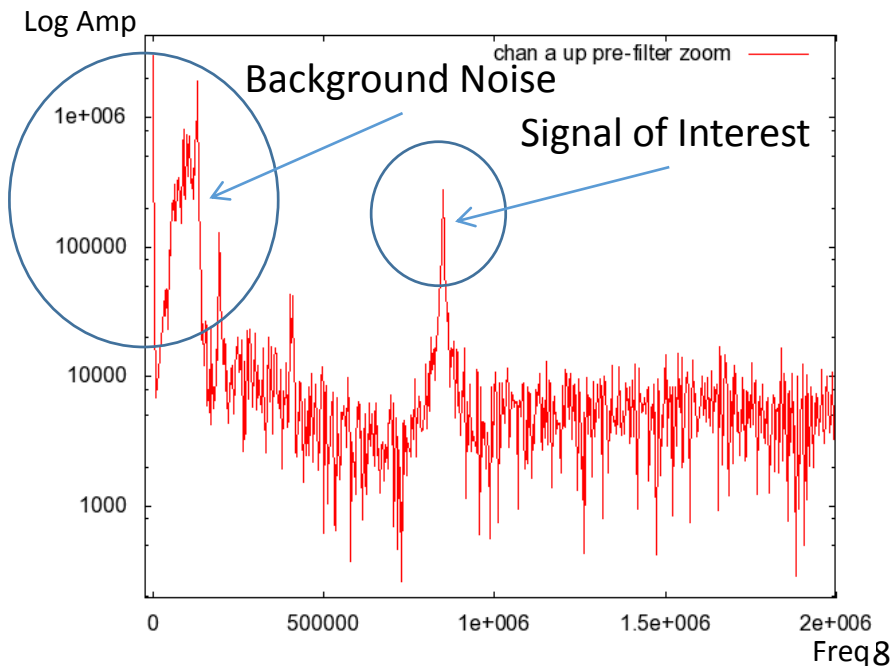


# Real-time Processor

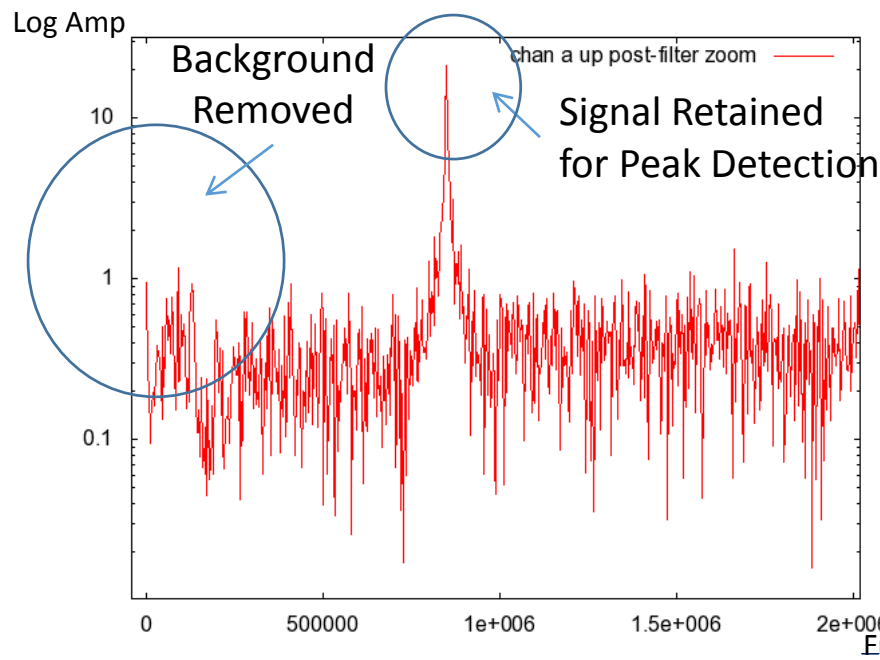


- Large FFT (576k points at 30 Hz)
- Reduced random noise and minimized sporadic frequency noises
- Noise whitening
- Minimized ambiguity and false alarms
- All components and subsystems controlled by C&DH unit
- Robust real-time processing and deterministic operational sequence are required for autonomous operation

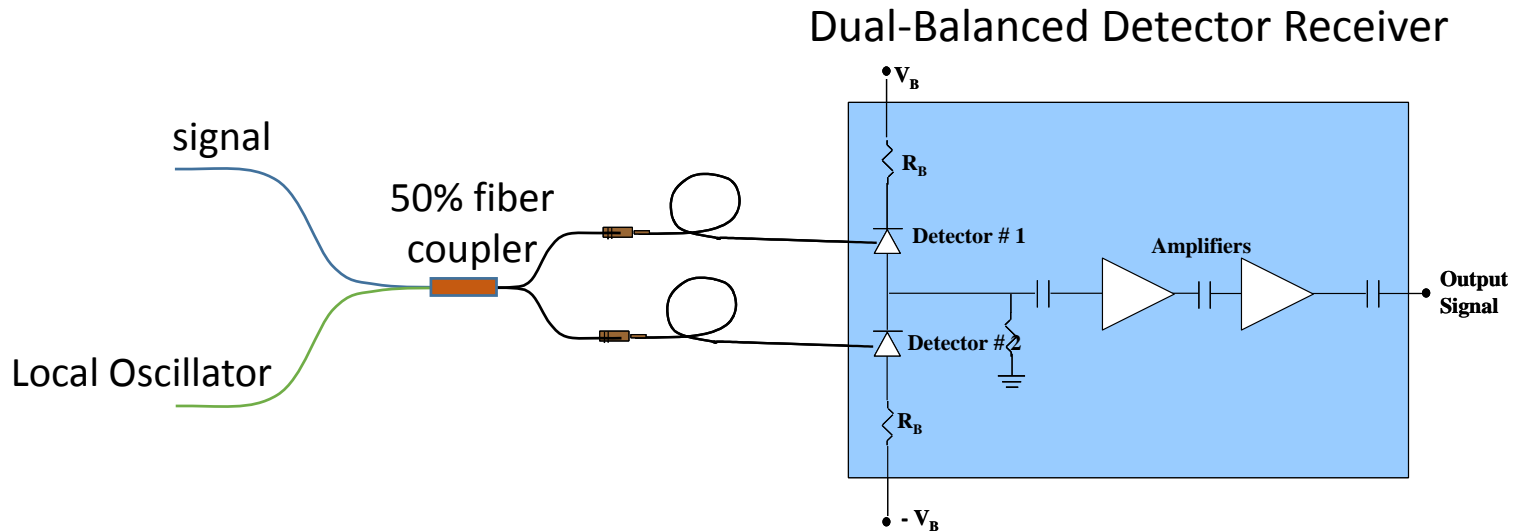
Before filter



After filter







Shot noise limited signal-to-noise ratio:

$$\frac{S}{N} = \frac{\rho P_s}{e \cdot B_e} F_0$$

$F_0$  accounts for the signal power reduction due to speckle, turbulence, and phase-front mismatch.

Heterodyne detection optimization is critical for effective operation:

- Optimum local oscillator power
- Balanced detectors
- Detector/amplifier impedance matching
- Transmit/receive Aperture size
- Beam collimation
- Signal averaging time

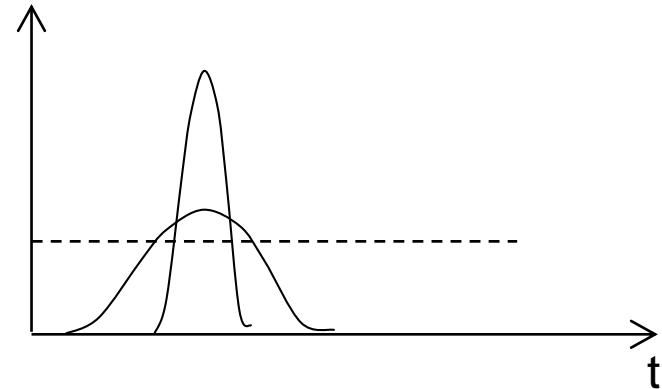


# NDL measurement performance



- Strength and width of the signal spectrum define maximum operational range
- Width of the signal spectrum depends on:
  - Seed laser linewidth
  - Modulation linearity
  - Vehicle vibration and angular motions

$$\partial f_{dSNR} = \frac{\sqrt{3}}{\pi \tau_p \sqrt{SNR}}$$





# NDL extensive testing over different phases of its development



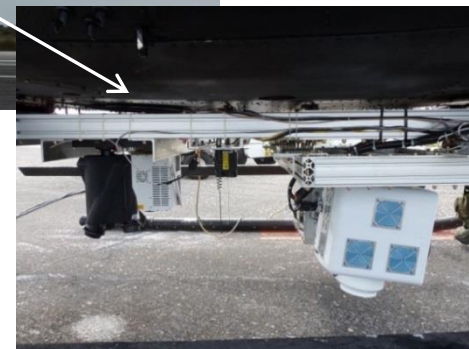
2008



2010



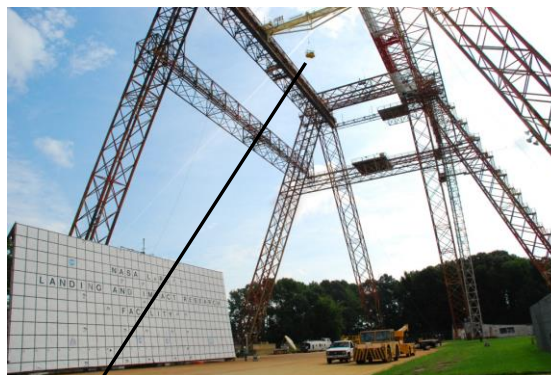
2012



Truck Tests

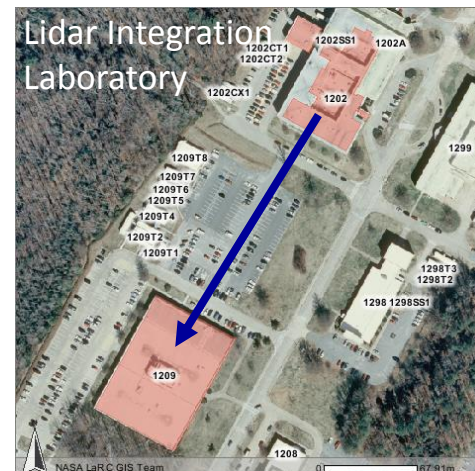


Gantry Tests



NDL  
Optical Head

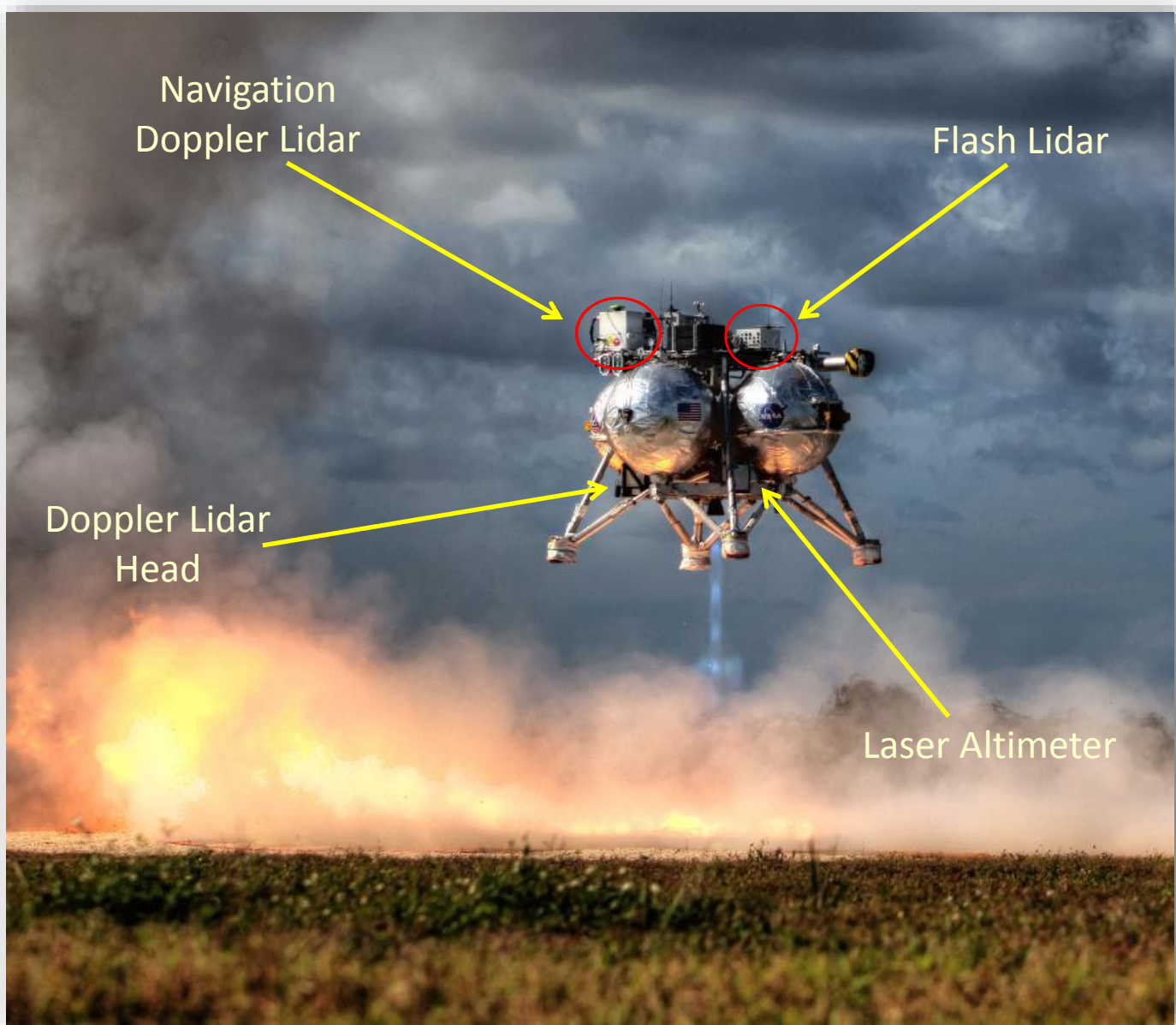
Lidar Integration  
Laboratory



LaRC



# Prototype Lidar Sensors Integrated with Morpheus Vehicle

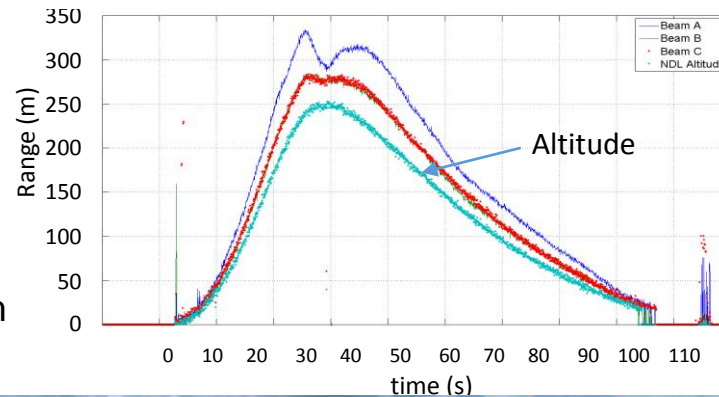
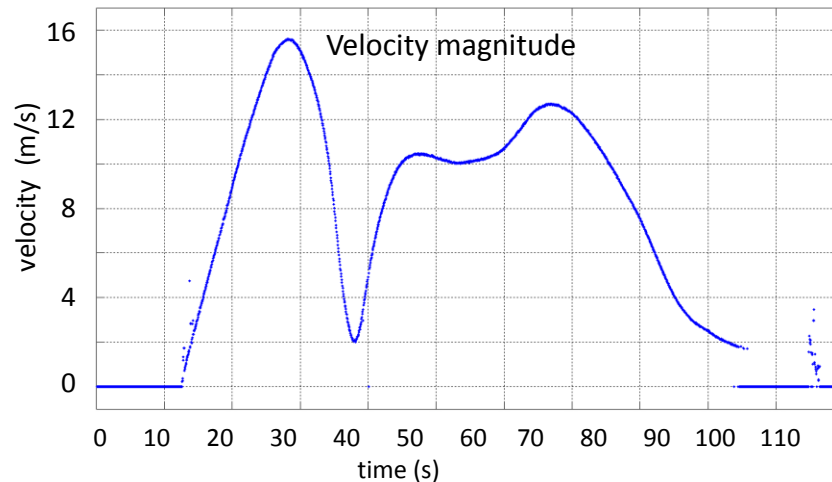
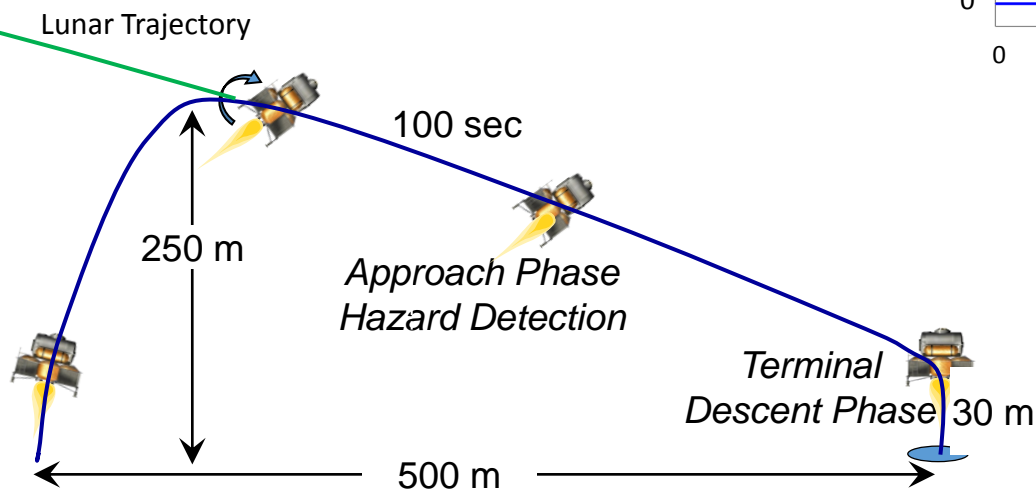




# Morpheus Closed-Loop Demonstration



- 3 open-loop flights
- 3 closed-loop flight
  - 2 in May and 1 in December
- NDL provided critical data for precision soft landing at selected site





# Next Generation NDL



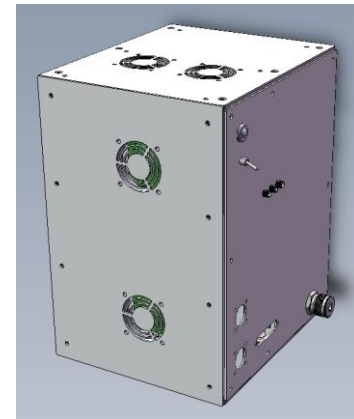
- Expansion of performance envelope and reduction in size, power, and mass are required for NDL's consideration for a wide range of landing missions including Mars
- Next generation NDL will be completed by Spring 2016
  - Max LOS velocity from 75 m/s to 200 m/s
  - Max LOS operational range in earth atmosphere from 2.5 km to 4 km
  - Half the size and mass
  - Flight-like design



Size: 44 x 38 x 16 cm



## Flight Prototype Unit



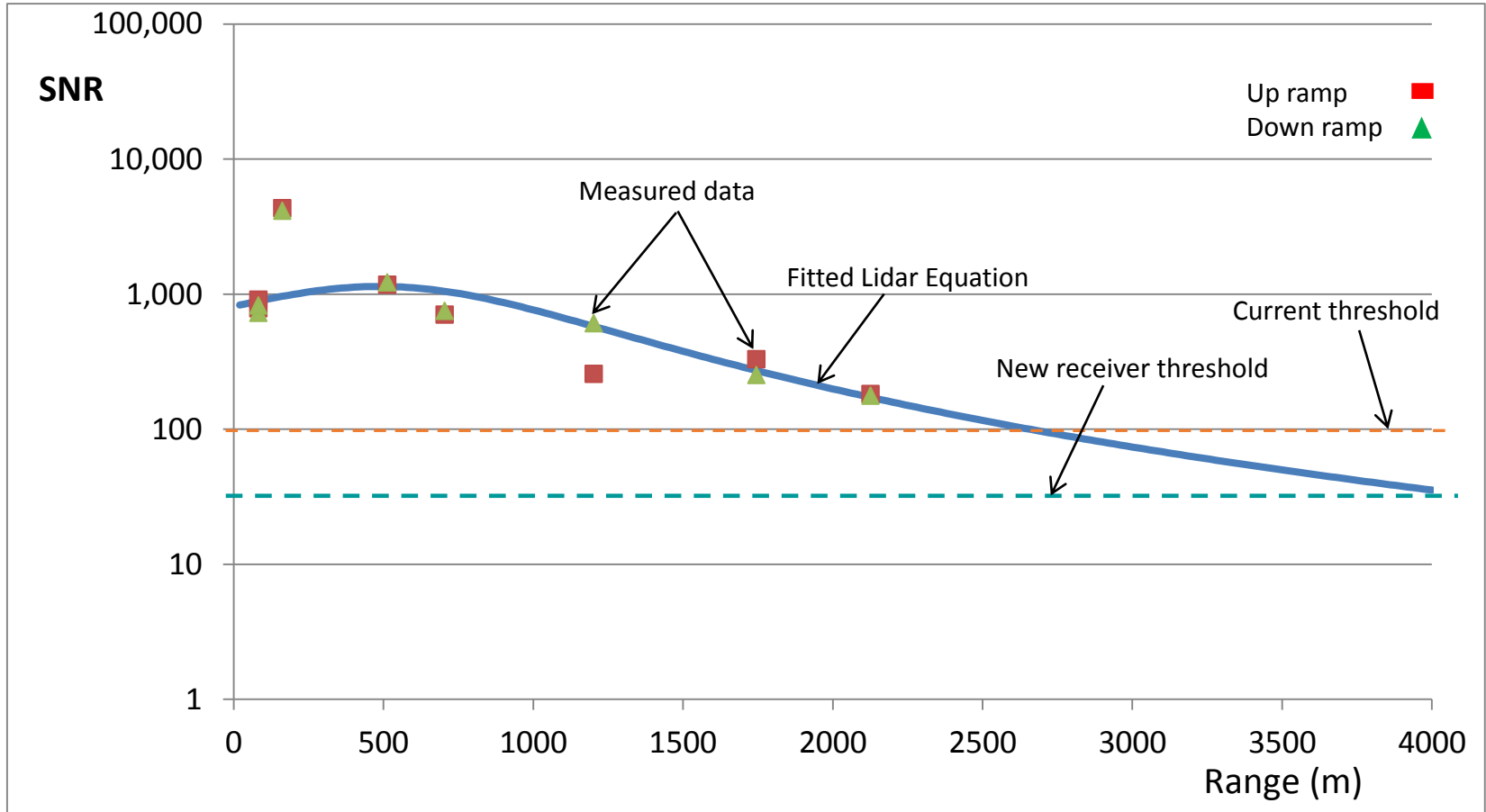
Size: 29 x 23 x 20 cm



# Max Operational Range



Measured operational range of NDL prototype





# Navigation Doppler Lidar Specifications



Parameter		Prototype	Next GEN
LOS Velocity Error		0.2 cm/sec	0.2 cm/sec
LOS Range Error		30 cm	30 cm
Maximum Operational Altitude		Earth 2500 m	4000 m
Maximum LOS Velocity		75 m/sec	200 m/sec
Data Rate		20 Hz	20 Hz
Dimensions	Electronic Chassis	44 x 38 x 16 cm	28 x 22 x 20 cm
	Optical Head	20 dia x 25 H cm	17 dia x 18 H cm
Mass	Electronic Chassis	16.4 kg <sup>1</sup>	10 kg
	Optical Head	5.2 kg	3 kg
Power (28 VDC)		95 W <sup>1</sup>	85 W

1. Heatsink and fans module add 4.9 kg and 55 W to current unit.

ALHAT  
Prototype built  
in 2012



Upgraded Unit will  
be completed by  
March 2016

**LaRC**





# SUMMARY

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- Completed two fully-autonomous, highly reliable, prototype units
- Demonstrated the capabilities of the NDL for NASA's landing application
- 3 helicopter flight test campaigns
- 5 open-loop flights onboard a rocket-powered free-flyer vehicle (Morpheus)
- 1 closed-loop flight onboard Morpheus operating with vehicle GN&C (December 2014)
- Ongoing Work
  - Develop next GEN system:
  - Enhance performance:
    - Increase maximum operational range from 2500 m to 4000 m and maximum velocity from 75 m/sec to 200 m/sec
    - Reduce size and mass by about 50%
  - Conduct a free-flyer test
  - Build an Engineering Developmental Model (EDU) for space-flights