Fiber-based Doppler Lidar for Vector Velocity and Altitude Measurements

Farzin Amzajerdian, Diego Pierrottet, Glenn Hines, Larry Petway, and Bruce Barnes

NASA Langley Research Center

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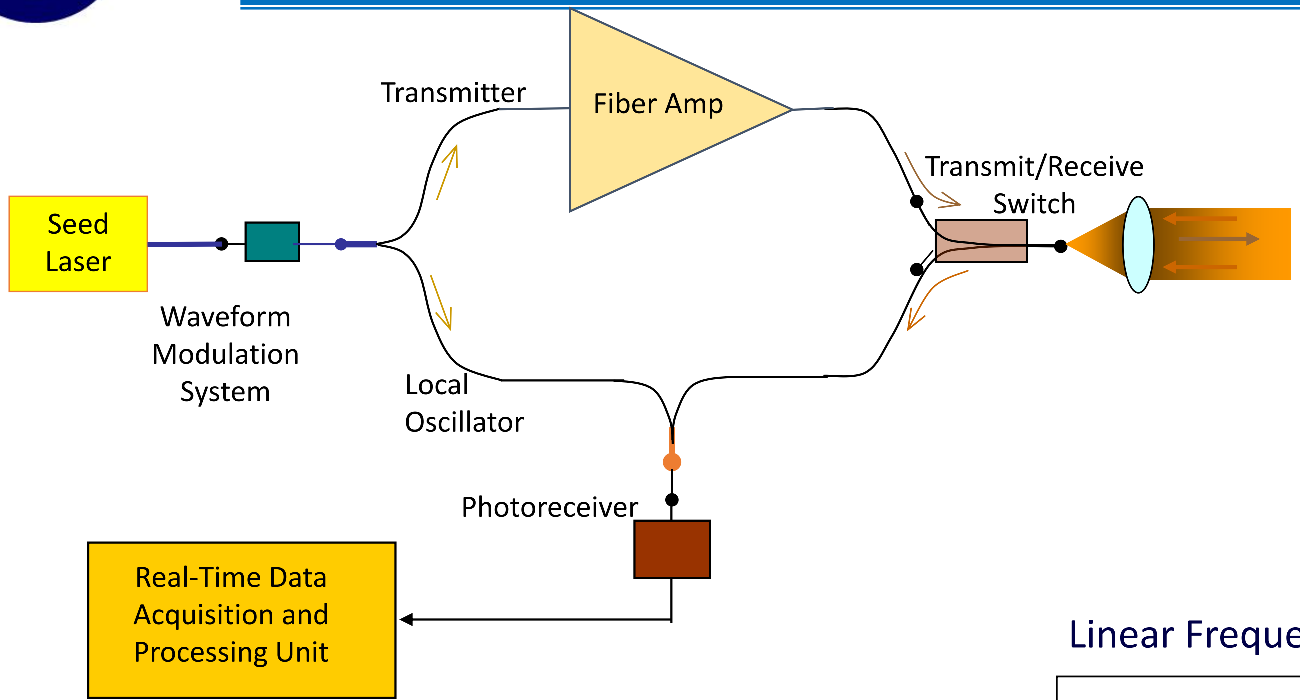
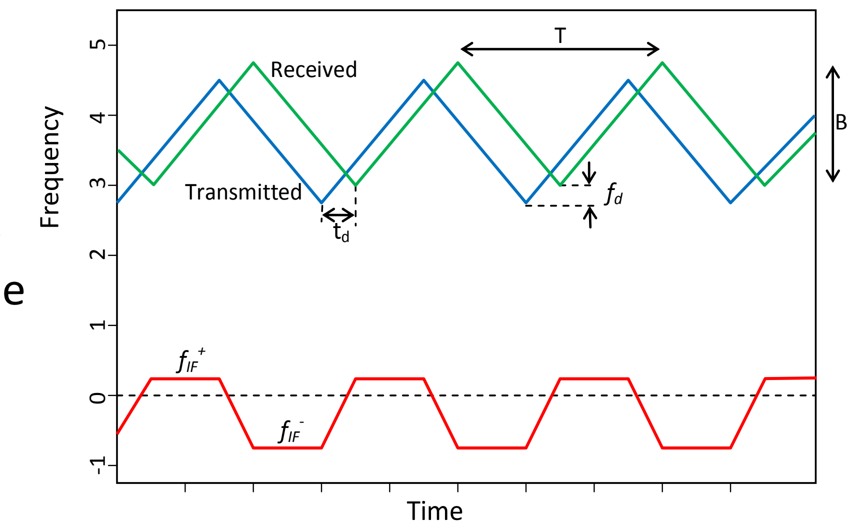
Navigation Doppler Lidar (NDL)

- 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

Principle of NDL



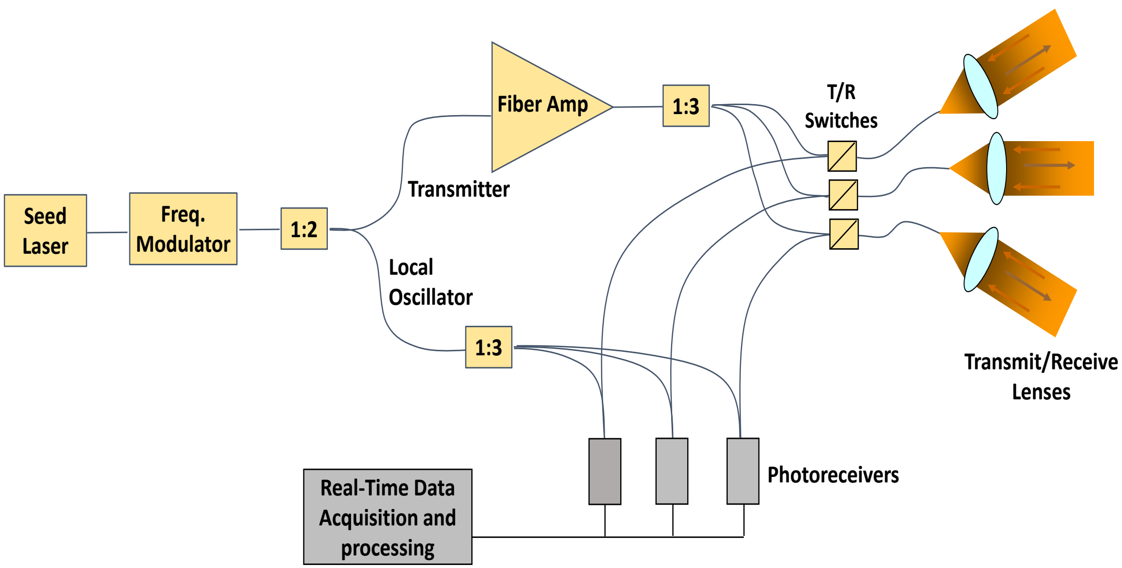
Linear Frequency Modulation Technique



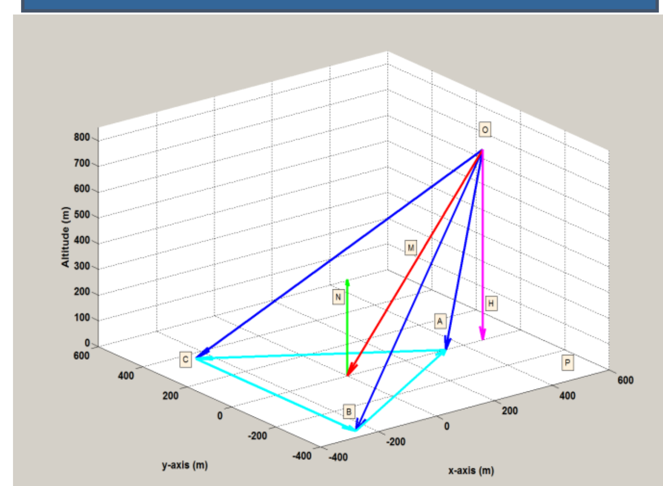
- Utilizes Doppler shift of scattered continuous-wave laser beam to measure velocity along the laser beam
- Application of a waveform modulation allows measuring range to ground

Navigation Doppler Lidar (NDL)

- 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 does not require attitude data from an IMU



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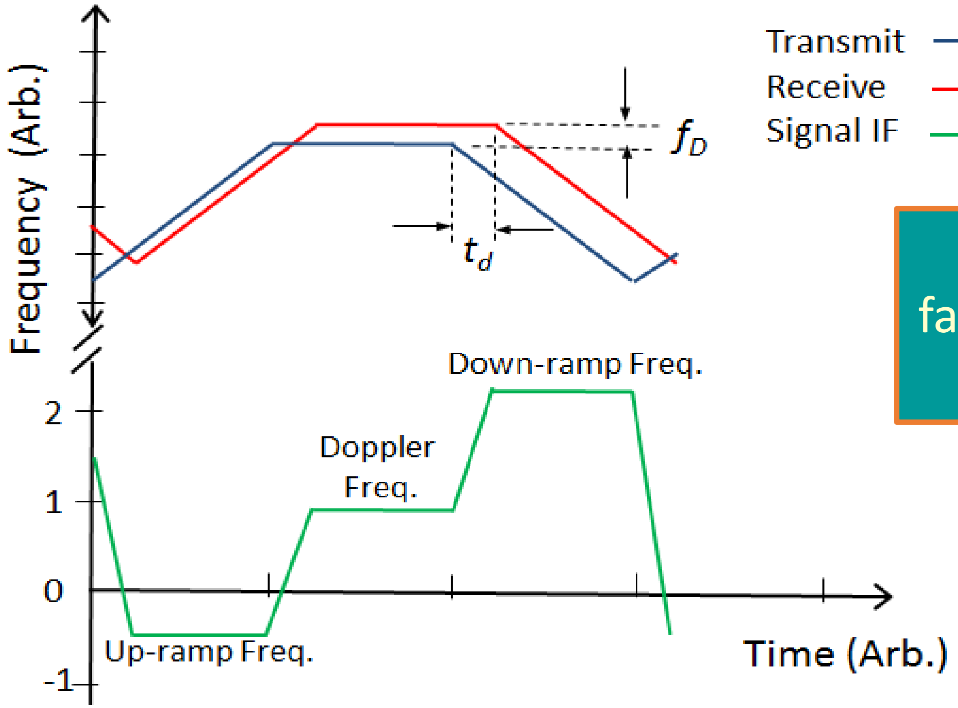
NDL prototype used for ALHAT tests

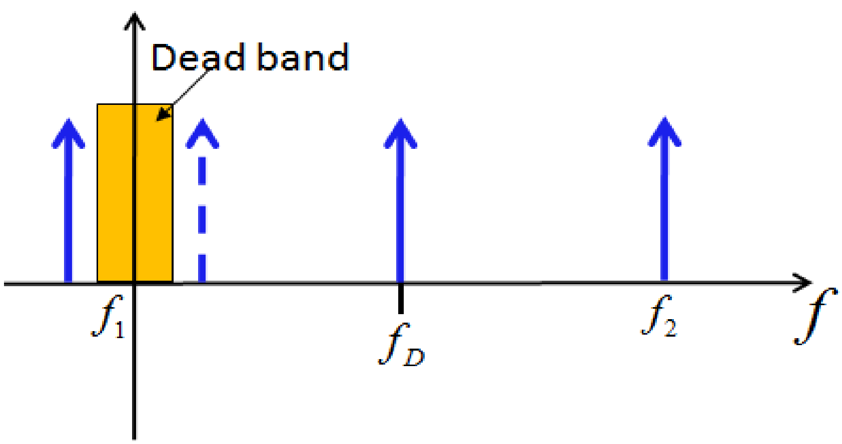
- Fully-autonomous operation
- Integrated real-time processors
- Subjected to thermal and vibration tests
- Helicopter and closed-loop Morpheus flight tests as an integrated sensor of the GN&C system

- 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



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

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

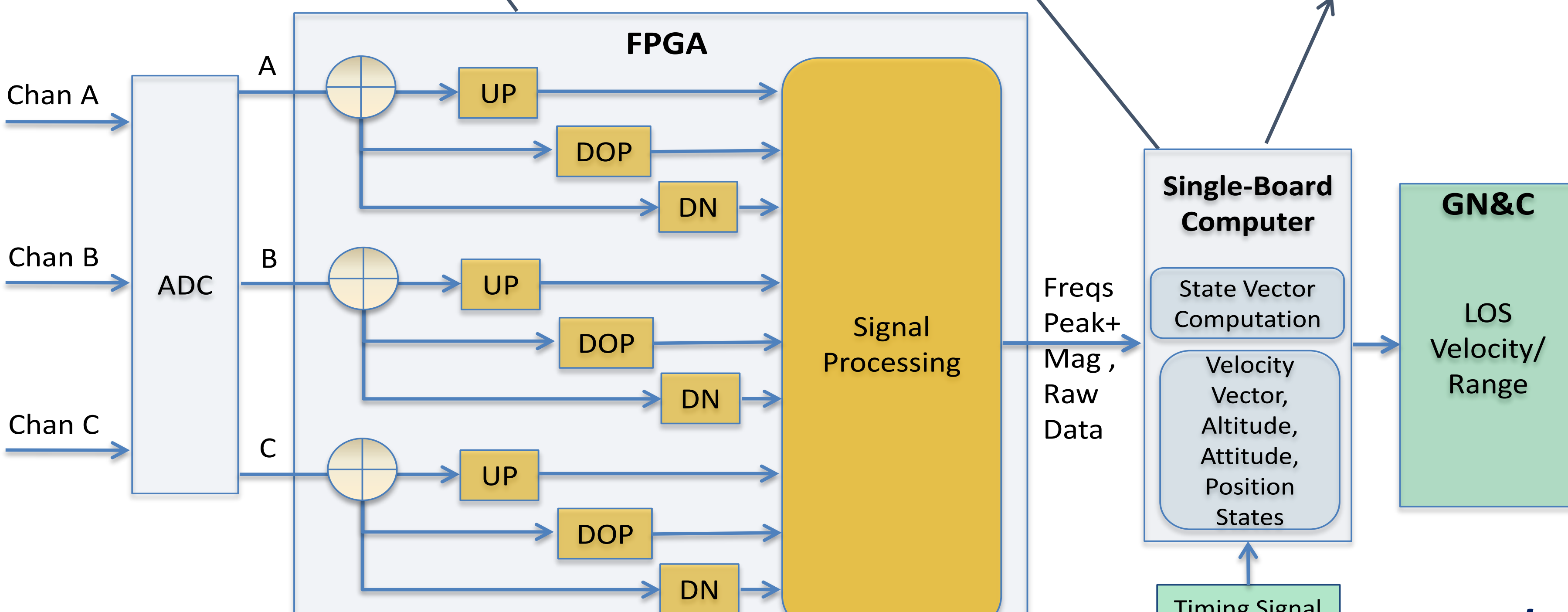
$$V = \left(\frac{\lambda}{2}\right)\left(\frac{f_{IF}^{+} + f_{IF}^{-}}{2}\right)$$

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



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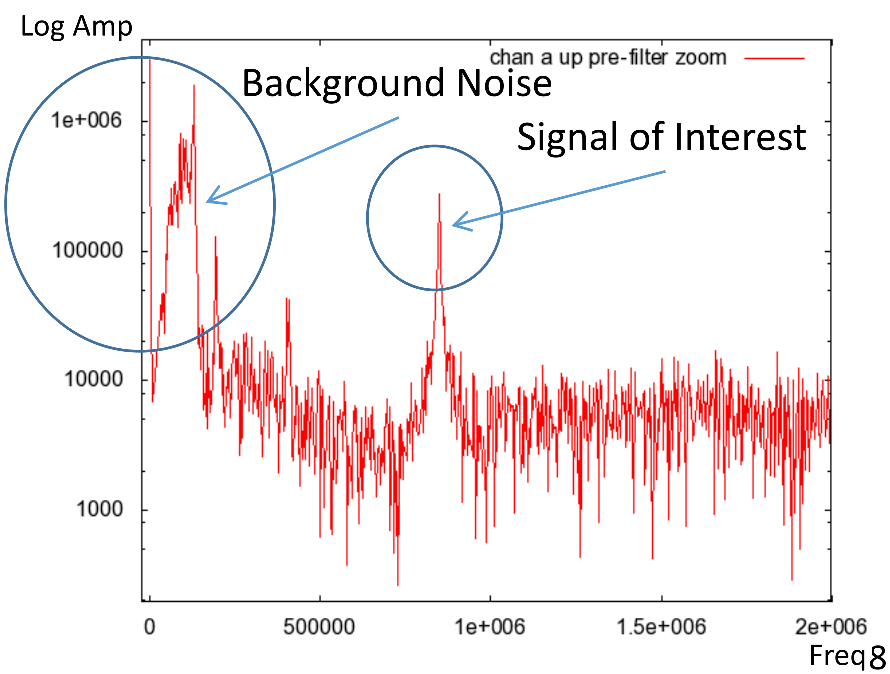
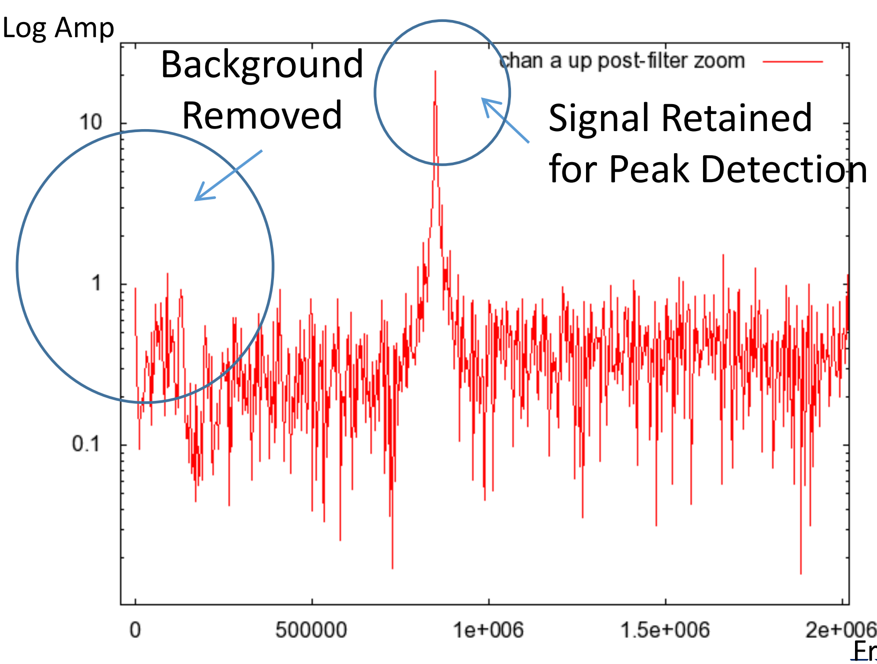
Real-time Processor

- 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

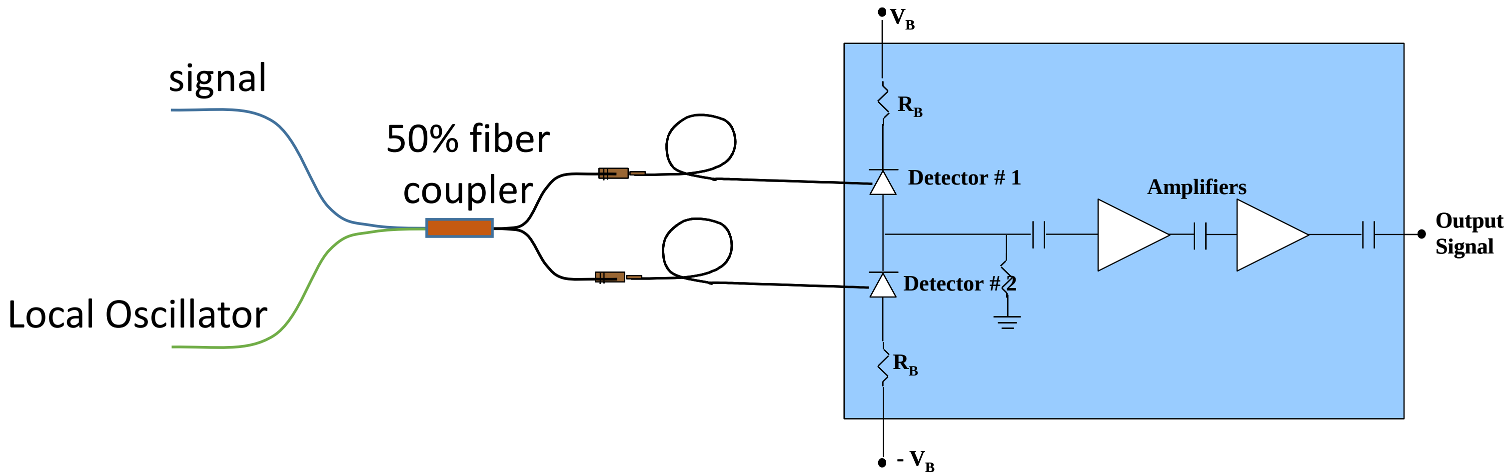


After filter



Optical Heterodyne Receiver Performance

Dual-Balanced Detector Receiver



Shot noise limited signal-to-noise ratio:

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

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

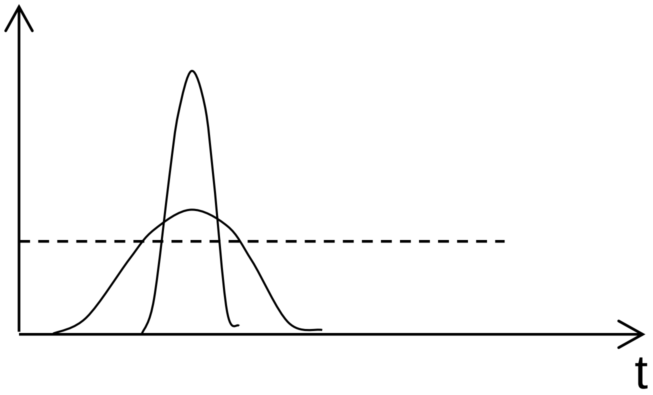
Heterodyne detection optimization is critical for effective operation:

- 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 linewdith
  - Modulation linearity
  - Vehicle vibration and angular motions

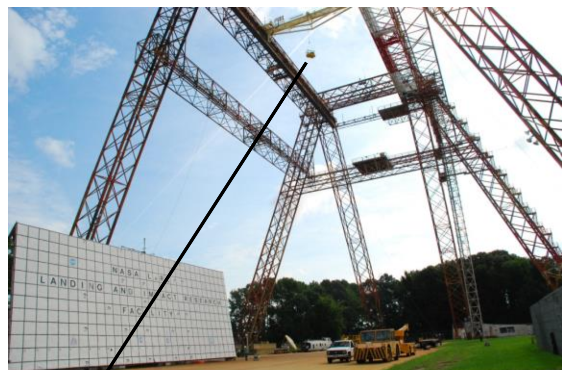
$$\partial f_{dSNR} = \frac{\sqrt{3}}{\pi \tau_p \sqrt{SNR}}$$

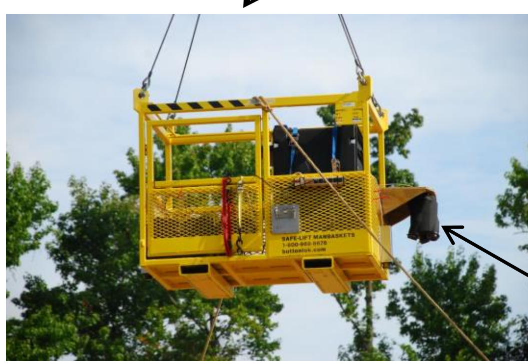


NDL extensive testing over different phases of its development

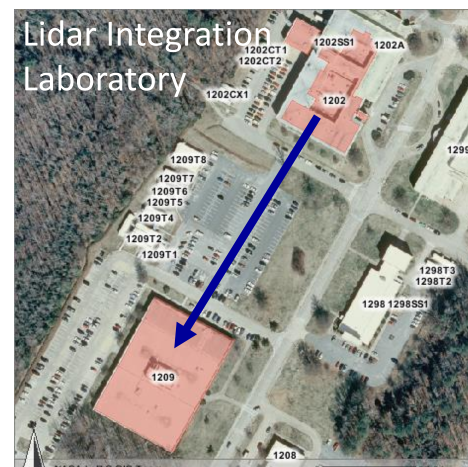
Truck Tests

Gantry Tests

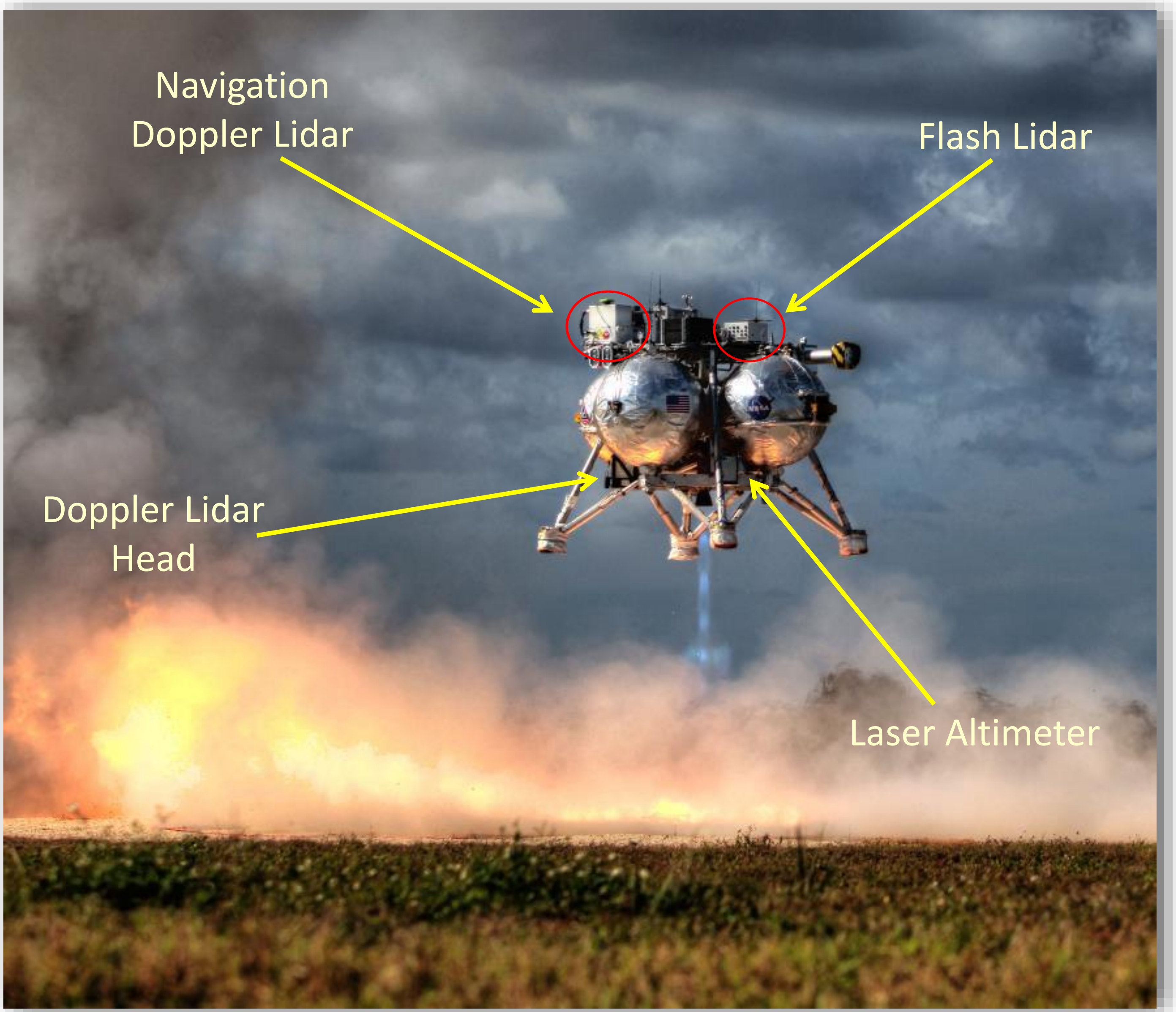




NDL
Optical Head



Prototype Lidar Sensors Integrated with Morpheus Vehicle



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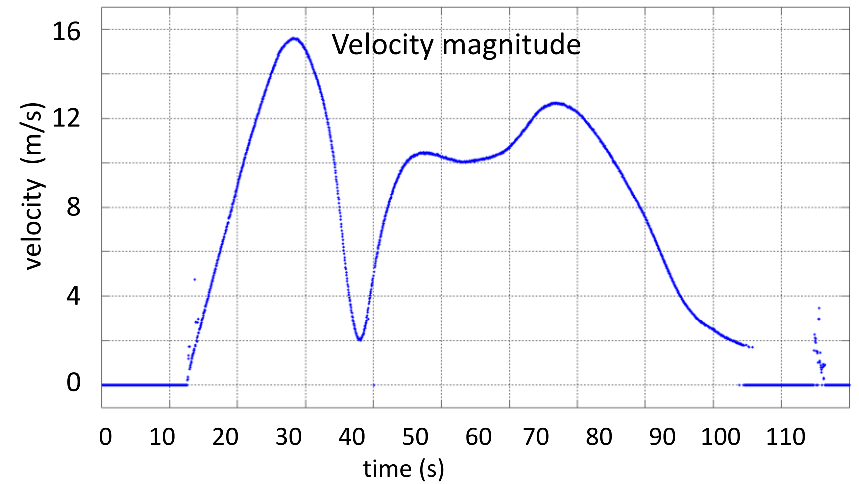
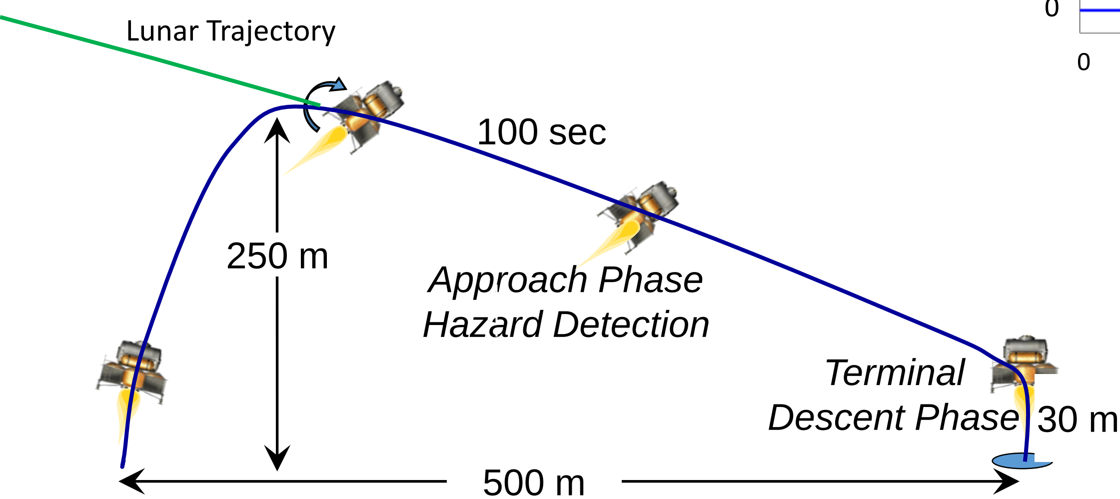
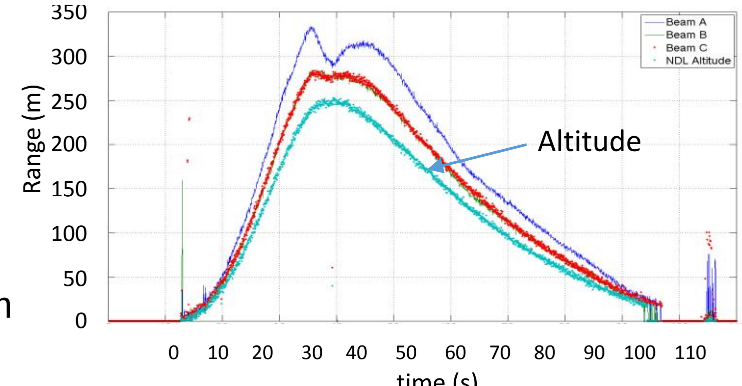
Morpheus Closed-Loop Demonstration

- 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





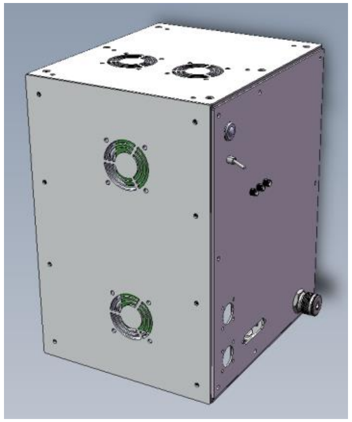


Next Generation NDL

- 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

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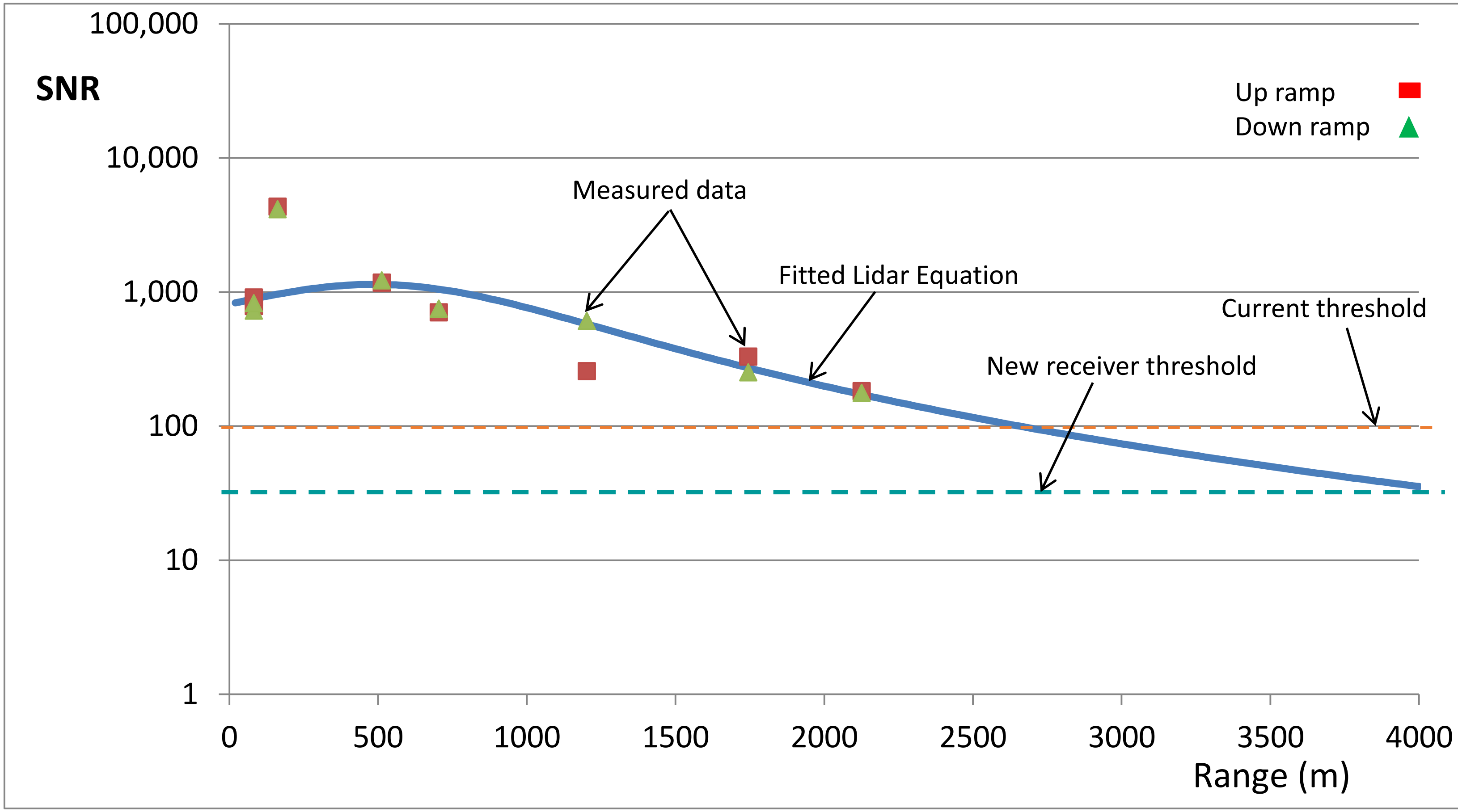
Max Operational Range

Measured operational range of NDL prototype



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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[1]	10 kg
	Optical Head	5.2 kg	3 kg
Power (28 VDC)		95 W[1]	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

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SUMMARY

- 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