

Coherent Doppler Lidar for Measuring Velocity and Altitude of Space and Aerial Vehicles

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ABSTRACT: A coherent Doppler lidar has been developed to support future NASA missions to planetary bodies. The lidar transmits three laser beams and measures line-of-sight range and velocity along each beam using a frequency modulated continuous wave (FMCW) technique. Accurate altitude and velocity vector data, derived from the line-of-sight measurements, enables the landing vehicle to precisely navigate from several kilometers above the ground to the designated location and execute a gentle touchdown. The same lidar sensor can also benefit terrestrial applications that cannot rely on GPS or require surface-relative altitude and velocity data.

Keywords: Coherent Laser Radar, Doppler Lidar, Precision Navigation, GPS-deprived Navigation

1. Introduction

Past robotic and manned planetary landing missions relied on radars for ground-relative velocity vector and altitude data during their descent phase starting at several kilometers above the ground. The Navigation Doppler Lidar (NDL), built and demonstrated by NASA Langley Research Center, presents a viable alternative to obsolete radar sensors. The NDL offers several critical advantages compared with radars, including significantly higher precision and reduced size, weight, and power. In addition, the laser-based NDL sensor does not suffer from measurement perturbation from terrain features or signal ambiguity from transmitted side lobes, and is far less susceptible to signal clutter, such as returns from the lander structure or jettisoned components [1]. The higher quality data provided by the NDL will enable a more precise navigation towards the designated landing site and a well-controlled touchdown (greater stability and lower impact loads) that translate to lower fuel reserve and smaller leg span thus further reducing the vehicle mass. Therefore, the NDL can potentially reduce the overall cost and risk of landing missions and enable new capabilities for planetary exploration missions including missions to the Moon, Mars, asteroids, and Jupiter moons [2].

The NDL can also benefit terrestrial applications such as aircraft navigation without reliance on external satellite signals. Conventional aircraft Guidance, Navigation, and Control (GN&C) systems combine the Inertial Measurement Unit (IMU) data with the signals from a Global Positioning System (GPS) to determine the vehicle position and velocity vector. An IMU has an excellent response to rapid motions but suffers from an accumulated error over time (drift) while GPS can provide accurate long-term data. However, the GPS signal can be blocked or jammed by intentional or unintentional interference causing significant deviation in the navigation solution.

2. Lidar System Description

Fig. 1(a) illustrates the NDL system design. The lidar uses a frequency modulated continuous wave (FMCW) technique and optical homodyne detection to obtain both range and velocity data. A relatively

low power, single frequency laser operating at an eye safe wavelength of 1.55 micron is used as the master oscillator. The frequency of this laser is modulated linearly with time. A portion of the laser power is amplified to be transmitted and the rest is used as the local oscillator (LO) for optical homodyne detection. The lidar transmits three laser beams into three fixed directions relative to each other, and the return signals are directed to three corresponding photo-receivers. The digitized outputs of the three photo-receivers are processed by a Fast Fourier Transform (FFT) algorithm to extract line-of-sight (LOS) velocity and range data. The platform vector velocity is determined from the LOS velocities measured along the three laser beams by using a priori pointing knowledge. Using all three simultaneous LOS range measurements allows determination of the vehicle altitude relative to the local ground without the need for vehicle attitude angle data from a separate sensor [3]. The use of three beams to compute altitude also reduces the effect of terrain features such as boulders and craters when compared to a single beam radar or lidar altimeter.

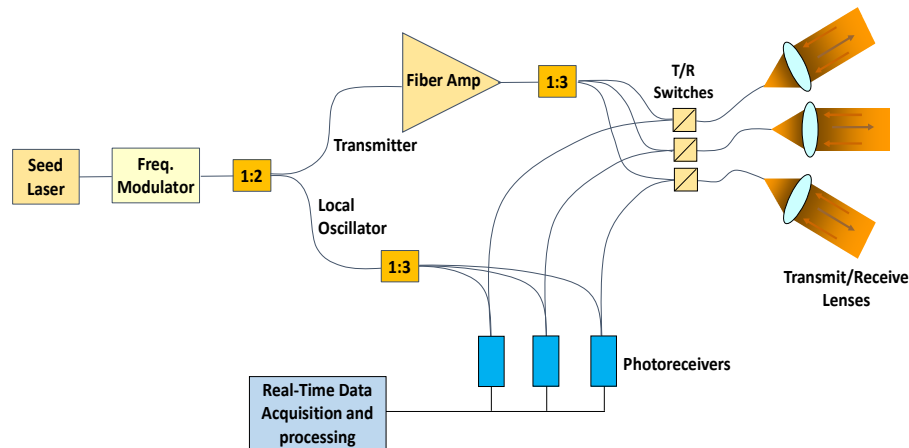


Figure 1. Doppler lidar system diagram.

Fig. 2 shows the prototype NDL, we refer to as generation 2 (GEN 2) unit, developed for a series of flight tests to demonstrate the capabilities of the NDL as a GN&C sensor. The prototype lidar consists of an electronics chassis and an optical head that houses three fiber-coupled lenses. The optical head is mounted rigidly on the vehicle with a clear field-of-view to the ground, and connected to the electronic chassis through a long fiber optic cable carrying the transmitted beams to the lenses and directing the collected signals from the same lenses to the receivers. The electronic chassis contains all the lidar components, including transmitter laser, receiver, real-time processor, system controller, and power supply unit. This prototype system is capable of measuring vehicle velocity and altitude with 0.2 cm/s and 30 cm resolution, respectively. The GEN 3 NDL currently under development will extend the NDL operational envelope increasing its maximum velocity from 70 m/s to 200 m/s and its maximum range from 2.5 km to over 4 km in order to meet the needs of a wide range of landing scenarios. The design upgrades being incorporated into the GEN 3 NDL will also result in about 40% reduction in size and mass compared with the GEN 2 instrument.



Figure 2. Prototype Doppler lidar system consisting of an electronic chassis and an optical head.

3. Flight Tests and Results

The capabilities of the Doppler lidar were evaluated and its performance characterized during different stages of its development through extensive laboratory experiments, dynamic testing on a swinging platform from the NASA LaRC gantry (a 240-foot high structure) and on a moving truck, and three helicopter flight test campaigns [3,4]. These tests led to the completion of the GEN 2 prototype unit and its demonstration onboard a rocket-propelled flight-test vehicle referred to as Morpheus (Fig. 3). The flight tests also included a 3-D imaging flash lidar and a long range laser altimeter that we developed under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project along with the NDL [2].

The demonstration flights were conducted in 2014 at the NASA Kennedy Space Center Shuttle Landing Facility. A 100 m x 100 m hazard field was constructed specifically for these flights that simulates a challenging lunar terrain consisting of realistic hazard features (rocks piles and craters) and designated landing areas. In this flight test campaign, the flash lidar identified the best safe landing site and reported its coordinates to the vehicle GN&C system. The data from the NDL was then used by the GN&C system to navigate and land the vehicle precisely at the selected location, avoiding the hazardous rocks and craters (Fig. 3b).

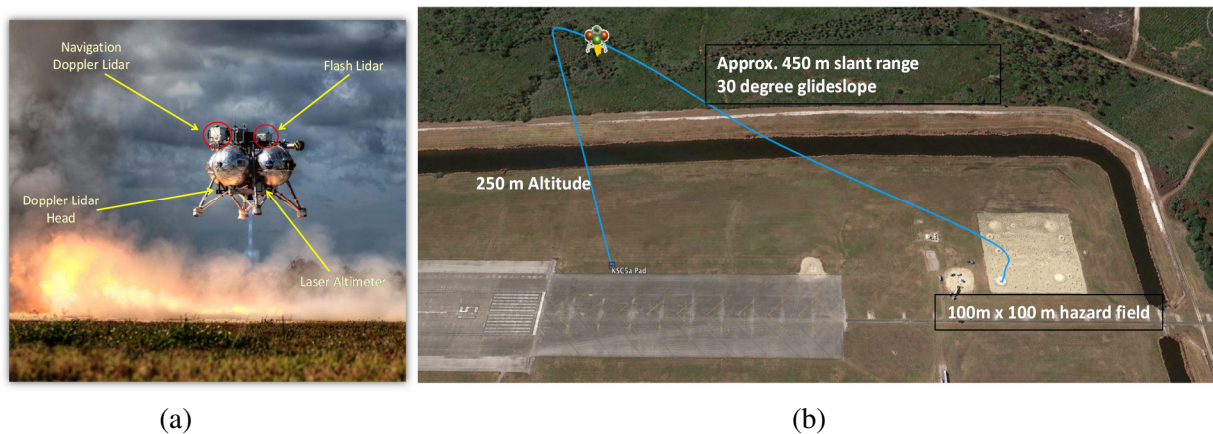


Figure 3. Closed-loop flight demonstration using rocket-propelled Morpheus vehicle. a) Doppler lidar along with 3-D flash lidar and long-range laser altimeter integrated into Morpheus; b) Navigating and landing in the hazard field using the Doppler lidar data.

Fig. 4 shows the NDL data from the last flight of a series of six flights onboard the Morpheus vehicle. The red curves on the left show the NDL LOS velocity for each of the three beams over the duration of the flight. The blue curves are the velocity estimates, projected along the lidar beams, from the vehicle navigation system (using GPS and IMU data) showing excellent agreement between them. The resolution of LOS velocity measurement is 2 mm/sec limited by the FFT processing algorithm. The NDL velocity precision, defined as random noise about its mean, was measured to be 1.7 cm/sec 1-sigma, dominated by the vehicle vibration. The velocity accuracy (bias) was estimated analytically to be about 1 cm/sec. The NDL velocity precision and accuracy demonstrated in the Morpheus flights are about an order of magnitude better than those required for precision and/or well-controlled soft landings. Fig 4 (right) provides the NDL altitude data for the same flight, showing the three LOS measurements of range to ground. One of the beams (blue curve) looking along the flight path measuring a longer distance while the other two beams (green and red) looking to the sides but still tilted forward have their measured plots almost overlap. From these three LOS range data, the vehicle altitude relative to local ground is calculated in real-time without attitude data from the IMU.

The plots of Fig. 4 show some data dropouts at beginning of the flight and the last few seconds of the flight due to the dense dust cloud created by the engine during takeoff and landing (Fig. 5). The loss of lidar data in dust plume was expected and the ALHAT landing system was designed to dead-reckon to a soft landing

by utilizing the precision vector vertical velocity provided by the NDL prior to the creation of dust plume during the final stage of descent.

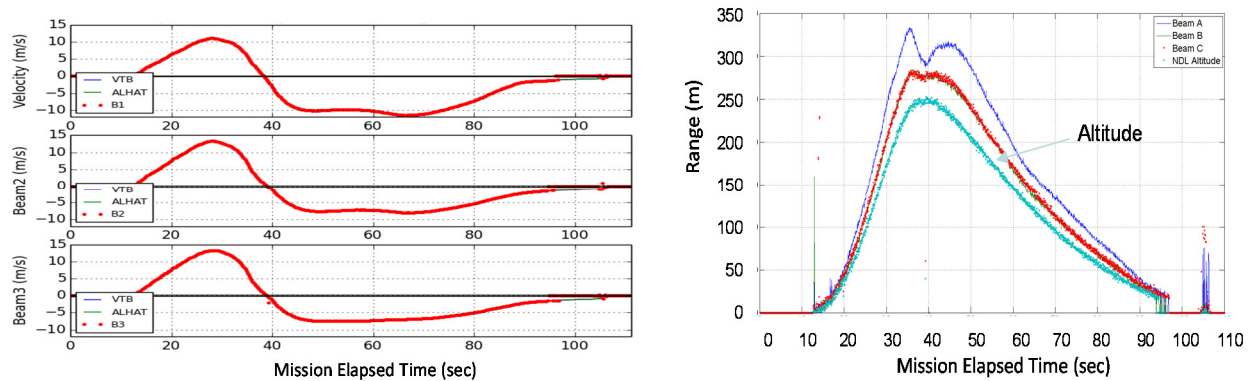


Figure 4. Morpheus flight test data: LOS velocity (left) and range (right).



Figure 5. Dust clouds created by the Morpheus engine during takeoff and landing.

4. Conclusion

The Navigation Doppler Lidar is expected to play a critical role in NASA's future planetary exploration missions because of its ability to provide the necessary data for precision navigation and executing well-controlled landings on solar system bodies. Compared to radars, the NDL offers more than an order of magnitude higher precision velocity and altitude data without concerns of measurement ambiguities or target clutter while significantly reducing the required mass, size, and power. The viability of this technology for future missions was demonstrated aboard a rocket-propelled free-flyer vehicle. The data from the NDL was used by an autonomous GN&C system to navigate and land the vehicle precisely at the selected site location surrounded by hazardous rock piles and craters. On a path to spaceflight units, we are currently developing the next generation NDL with an extended operational envelope and reduced size, mass, and power.

5. References

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