Doppler Lidar Sensor for Precision Navigation in GPS-Deprived Environment

F. Amzajerdian*[a], D. F. Pierrottet[b], G. D. Hines[a], L. B. Petway[a], and B. W. Barnes[a]
[a]NASA Langley Research Center, Hampton, VA 23681; [b]Coherent Applications Inc., Hampton, VA 23666.

ABSTRACT

Landing mission concepts that are being developed for exploration of solar system bodies are increasingly ambitious in their implementations and objectives. Most of these missions require accurate position and velocity data during their descent phase in order to ensure safe, soft landing at the pre-designated sites. Data from the vehicle's Inertial Measurement Unit will not be sufficient due to significant drift error after extended travel time in space. Therefore, an onboard sensor is required to provide the necessary data for landing in the GPS-deprived environment of space. For this reason, NASA Langley Research Center has been developing an advanced Doppler lidar sensor capable of providing accurate and reliable data suitable for operation in the highly constrained environment of space. The Doppler lidar transmits three laser beams in different directions toward the ground. The signal from each beam provides the platform velocity and range to the ground along the laser line-of-sight (LOS). The six LOS measurements are then combined in order to determine the three components of the vehicle velocity vector, and to accurately measure altitude and attitude angles relative to the local ground. These measurements are used by an autonomous Guidance, Navigation, and Control system to accurately navigate the vehicle from a few kilometers above the ground to the designated location and to execute a gentle touchdown. A prototype version of our lidar sensor has been completed for a closed-loop demonstration onboard a rocket-powered terrestrial free-flyer vehicle.

Keywords: Lidar, Laser Remote Sensing, Doppler, Ladar, Precision Navigation, Landing

1. INTRODUCTION

Future robotic and manned exploration missions to the Moon, Mars, and other planetary bodies demand accurate knowledge of ground relative velocity and altitude in order to ensure soft landing at the designated landing site[1,2]. Some missions may even require landing within a few meters of pre-deployed assets or landing in a small area surrounded by rocks, craters, or steep slopes[3-5]. To meet these requirements, a Doppler lidar is being developed by NASA under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project[5,6].

The Doppler lidar will begin its operation during the powered descent phase of a landing from an altitude of a few kilometers above the ground. The Guidance, Navigation, and Control (GN&C) system processes the lidar data to improve the vehicle position data from the Inertial Measurement Unit (IMU) that after long travel time from Earth are grossly inaccurate by hundreds of meters. The improved position knowledge along with the lidar precision vector velocity data enables the GN&C system to continuously update the vehicle trajectory toward the landing site. In addition to the precision trajectory determination, the lidar data will play an important role in performing a soft landing maneuver. For example, large robotic or manned vehicles must control their horizontal and vertical velocities to better than 1 m/s in order to avoid the risk of tipping over and to ensure a gentle touchdown. Control to these limits will require measurement accuracies to better than 0.5 m/s. Our Doppler lidar exceeds these requirements by about two orders of magnitude.

The Doppler lidar transmits three laser beams which are separated 120 degrees from each other in azimuth and are pointed 22.5 degrees from nadir. The signal from each beam provides the platform velocity and range to the ground along the laser line-of-sight (LOS). The LOS velocity and range precisions of the lidar have been measured to be approximately 3 mm/sec and 17 cm respectively. The six LOS measurements are then used to derive the three components of the vehicle velocity vector, and its altitude and attitude relative to the ground below.

Past landing missions, including Surveyor, Apollo, Viking, Phoenix, and Mars Science Laboratory[7,8], relied on radar technology for the altitude and velocity data. Doppler lidar offers major benefits including lower mass and smaller size, higher precision and data rate, and much lower false alarm rates. The Doppler lidar can also benefit terrestrial applications such as aircraft navigation without reliance on external satellite signals and landing on moving platforms (ships and aircraft carriers). Conventional aircraft GN&C systems combine the Inertial Measurement Unit (IMU) data with the signals from a Global Positioning System (GPS) to generate its state vector (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. Also, GPS position (altitude) data is referenced to sea-level and is of limited value when landing on a moving platform or in limited visibility conditions, or when autonomous navigation and landing is required.

2. SYSTEM DESCRIPTION

The Doppler lidar utilizes a frequency modulated continuous wave (FMCW) technique to obtain high-resolution range and velocity information. The principle of the lidar operation is illustrated in Fig. 1 showing the modulation waveform consisting of three segments: up-ramp chirp, constant frequency, and down-ramp chirp. The resultant returned waveform from the target is delayed by t_d, the light round trip time. When the target or the lidar platform is not stationary during the beam round trip time, the signal frequency will be also shifted up or down, depending on the velocity direction, due to the Doppler effect. When mixing the two waveforms at the detector, an interference signal is generated whose frequency is equal to the difference between the transmitted and received frequencies. In absence of velocity along the laser beam, the signal frequency during the "up-ramp" and "down-ramp" periods are equal and their magnitude is directly proportional to the distance to the target. When the vehicle is moving, the up-ramp and down-ramp frequencies will not be equal and their difference is related to the Doppler velocity. The target range and magnitude of the velocity component along the laser beam are determined through the following simple equations:

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

where f_{IF}^{+} and f_{IF}^{-} are the intermediate up-ramp and down-ramp frequencies, B is the modulation bandwidth, T is the waveform period, C is the speed of light, and λ is the laser wavelength.

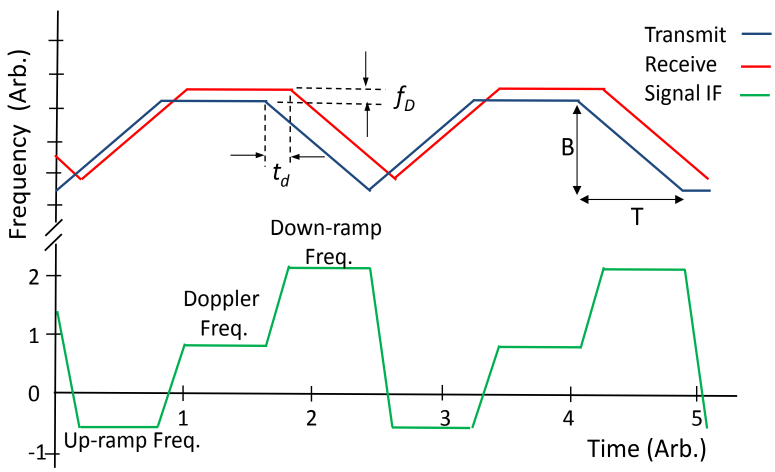

Figure 1. Linearly frequency modulated transmitted beam and returned signal, and the resulting intermediate frequency (IF) of the homodyne signal.

The constant frequency segment also produces the Doppler velocity that can be used for eliminating the data dropouts when either up-ramp or down-ramp frequency is very close to zero and allows for minimizing the measurement ambiguities that may arise in certain scenarios.

Figure 2 illustrates the system design utilizing an optical homodyne configuration. A relatively low power, single frequency laser operating at eye safe wavelength of 1.55 micron, is used as the master oscillator. The output of this laser is modulated per the waveform of Figure 1. Part of the laser output is amplified to be transmitted and the remaining is used as the local oscillator (LO) for optical homodyne detection. The lidar transmits three laser beams in different directions and the returns are directed to three corresponding receivers. In the current system, the transmitted beams make a 45-degrees cone angle which is chosen as a compromise between horizontal velocity accuracy which favors large angles, and higher operational altitude which is inversely proportional to the beam nadir pointing angle.

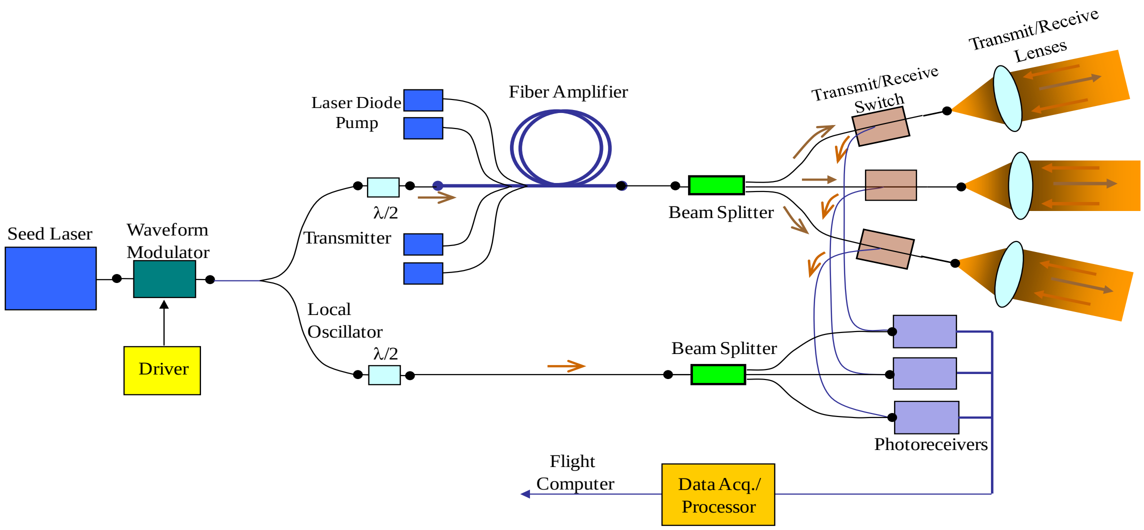

Figure 2. Doppler lidar system configuration illustrating three transmitted beams and their corresponding receivers providing line-of-sight velocity and range measurements in three different directions.

A single board computer (SBC) is used as the Command and Data Handling (C&DH) system which responds to commands from the vehicle, transmits the instrument's measurements, interfaces to the real-time processor, and controls and monitors the internal components of the lidar. The Doppler lidar signal processor digitizes and processes the output of three optical receivers in real-time. A functional block diagram of the lidar signal processor is shown in Figure 3. The primary electronic data processing component of the Doppler lidar is a field programmable gate array (FPGA) board. The digitized outputs of the three analog receivers are de-multiplexed in the time domain to separate the up-ramp, constant (Doppler), and down-ramp portions of the signal. The FPGA then applies a set of high-resolution fast Fourier transforms (FFT) to each segment of the waveform for each of the three beams. From these measured frequencies, the LOS velocity and range data are determined. The platform vector velocity is obtained from the LOS velocities measured along the three laser beams by using a priori pointing knowledge. Using all three 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. The use of three beams also reduces the effect of terrain features such as boulders and craters on the altitude data. Additionally, the vehicle attitude relative to the ground can be derived from the three LOS range measurements.

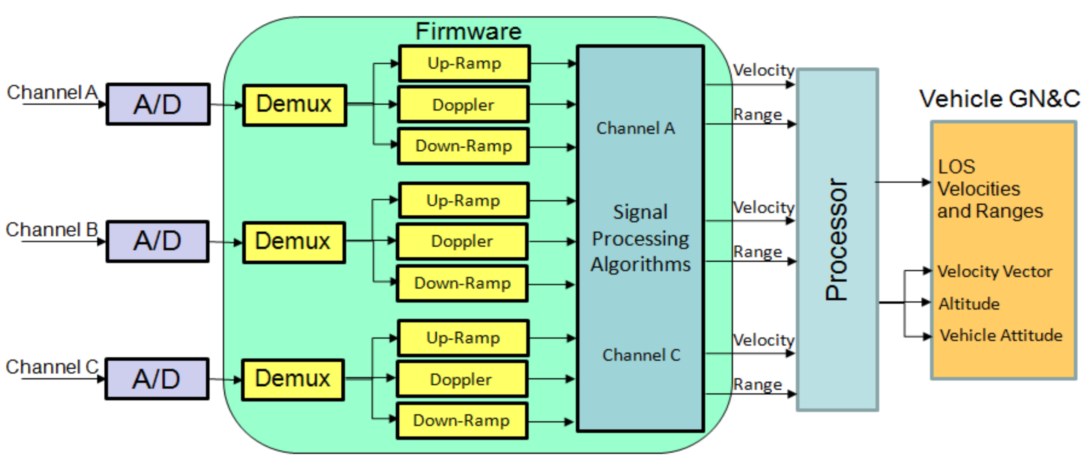

Figure 3. Real-time signal processor functional diagram.

3. SYSTEM DEVELOPMENT AND DEMONSTRATION

The capabilities of the Doppler lidar were evaluated and its performance characterized through three helicopter flight test campaigns held at NASA Dryden and NASA Kennedy Space Center (KSC). The first test was conducted in 2008 using a breadboard version of the lidar. For the second test in 2010, the lidar was engineered to a relatively compact package while improving its operational performance. Detailed description of the these two helicopter flight tests and their results are provided in referenced publications[9,10]. The third flight test was conducted in December 2012 using a prototype version of the Doppler lidar. As shown in Figure 4, the prototype system 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.

Figure 4. Prototype Doppler lidar system consisting of an electronic chassis and an optical head. All the lidar components, including transmitter laser, receiver, and real-time processor, are housed in the electronic chassis. The optical head, housing the three transmit and receive lenses, is rigidly mounted to the platform body with a clear view of the ground and connected by an armored fiber cable to the electronics chassis.

Figure 5 shows the lidar installation configuration on the helicopter platform during the latest flight test over a simulated lunar terrain facility at NASA Kennedy Space Center. The data from the last helicopter test indicate excellent performance and reliable operation over the two week duration of the campaign.

Figure 5. Helicopter flight test of Doppler lidar at NASA-KSC in 2012, along with other sensors and landing avionics developed under ALHAT project.

Figure 6 gives an example of the lidar data from this helicopter flight test. The lidar data was provided to a GN&C system, built specifically for landing applications, to be processed by its navigation filter. The performance of the GN&C system, operating in open-loop (not used by the helicopter), is currently being analyzed in a simulated landing vehicle environment.

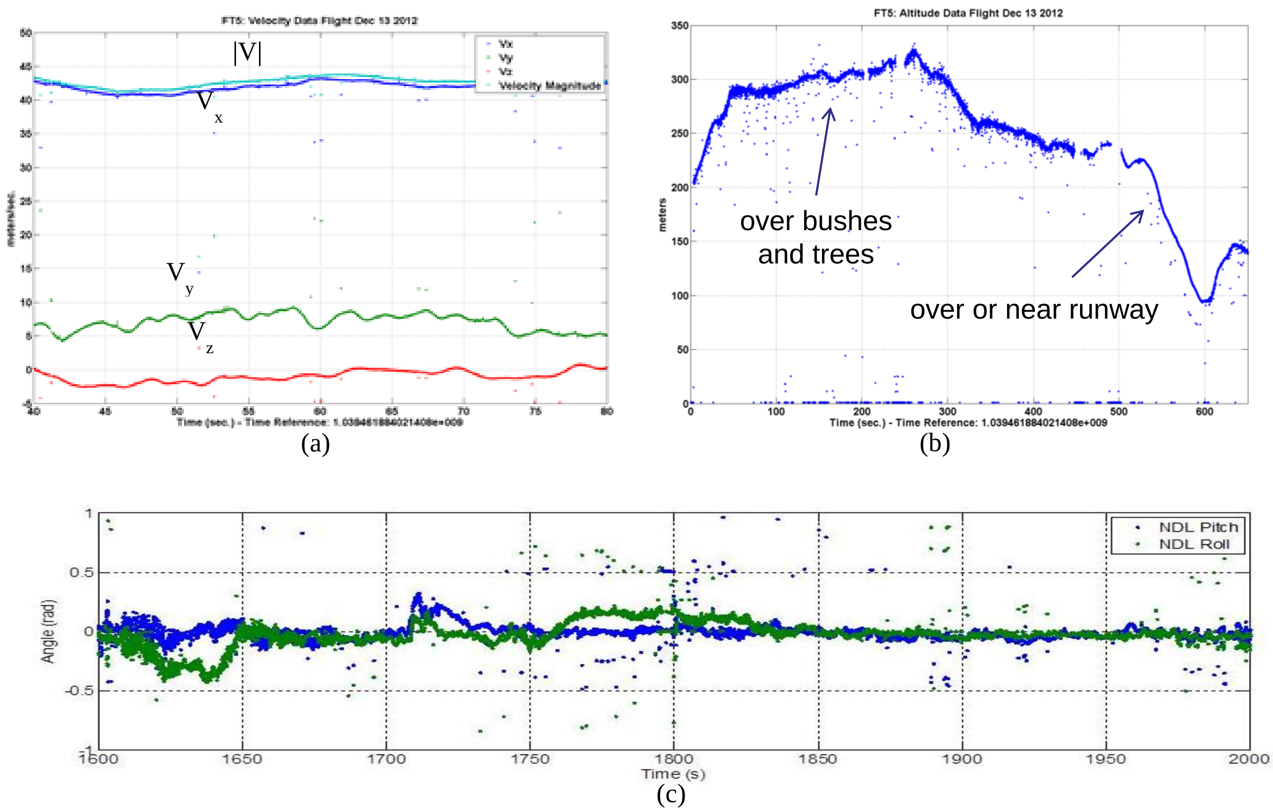

Figure 6. Example of the non-filtered helicopter flight test data. (a) 3 components of the velocity vector and its magnitude, (b) Altitude measurements showing the effect of tall vegetation and the data from short grass terrain and concrete surface, (c) platform pitch and roll angles.

The same Doppler lidar will be integrated into a rocket-powered terrestrial free-flyer vehicle (see Figure 7) for a full landing demonstration in the summer of 2013 at a simulated lunar terrain site consisting of realistic hazard features and a few safe landing areas[11]. The test vehicle, referred to as Morpheus[12], is being built by NASA Johnson Space Center (JSC) to demonstrate advanced propulsion and GN&C technologies for future landing missions. The lidar will be operating in a closed-loop with the GN&C system that controls the vehicle flight trajectory to the selected safe site and executes the landing maneuver.

4. Summary

A fiber-based coherent Doppler lidar, utilizing an FMCW waveform, has been under development at NASA Langley Research Center (LaRC) for the past several years. The capabilities of this system were demonstrated during its different stages of its development at LaRC's lidar test facility and through three helicopter flight test campaigns. This 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 in the GPS-deprived environment of space and for landing at designated locations on solar system bodies (the Moon, Mars, Asteroids, etc.). Compared to radars, the Doppler lidar can provide 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 landing missions will be demonstrated later this year through a series of tests aboard a rocket-powered free-flyer vehicle. In these flights, the Doppler lidar will be operating in a closed-loop with the vehicle's guidance, navigation, and control unit to execute precision landing at a simulated lunar terrain site.

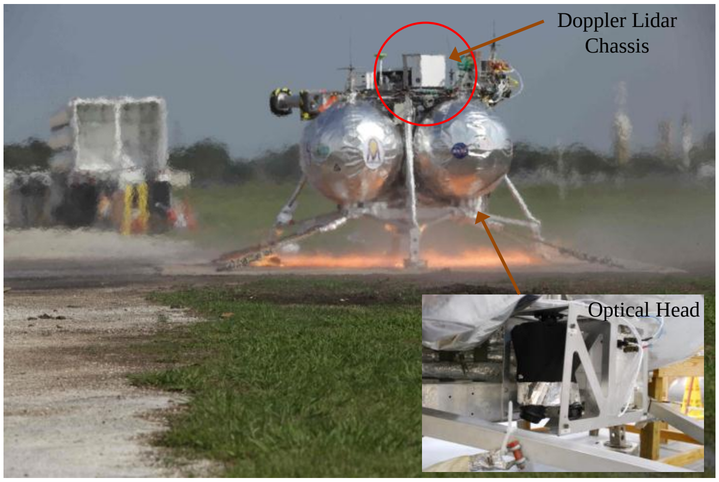

Figure 7. Prototype Doppler Lidar on Morpheus free-flyer vehicle during a hot fire test.

Acknowledgments

The authors are grateful to ALHAT project manager, Chirold Epp, NASA Johnson Space Center, for his guidance and support. We also would like to thank NASA's Advanced Exploration Systems (AES) program office for their continued support. The authors also acknowledge the ALHAT team members from NASA Johnson Space Center and NASA Jet Propulsion for their collaboration, and Gregory Gaddis for facilitating the helicopter flight test at NASA Kennedy Space Center.

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