Development of a Coherent Doppler Lidar for Precision Landing on Planetary Bodies

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Abstract: A coherent Doppler lidar has been developed by NASA for providing vector velocity and altitude data to landing vehicles. Future robotic and manned missions to planetary bodies demand precise ground-relative velocity and altitude data to execute complex descent maneuvers for safe, soft and pinpoint landing at a pre-designated site. Operating from over five kilometers altitude, this lidar provides velocity and range data within a few cm/sec and a few meters precision, respectively, depending on the vehicle dynamics. Two upcoming lunar landing missions will serve as the technology demonstration for robotic and manned landing missions to the Moon, Mars, and other solar system destinations. This paper describes the lidar design and its expected performance on landing vehicles.

Keywords: Coherent Laser Radar, Navigation Doppler Lidar, Precision Navigation, Precision Landing, FMCW Lidar, GPS-Deprived Navigation.

1. Introduction

A coherent Doppler lidar has been developed to address the need for a high-performance, compact, and cost-effective velocity and altitude sensor onboard landing vehicles. Future robotic and manned missions to solar system bodies require precise ground-relative velocity vector and altitude data to execute complex descent and soft landing maneuvers. This lidar sensor is designed to meet the performance requirements of a wide range of landing missions while complying with vehicle size, mass, and power constraints.

Global Positioning System (GPS) is commonly used in terrestrial navigation for vehicle position and velocity knowledge. In the absence of a GPS signal, past landing missions to planetary bodies primarily relied on radar to provide the necessary data to execute descent and landing maneuvers.[1-2] Our coherent Doppler lidar, called Navigation Doppler Lidar (NDL), offers several critical advantages compared to radar, including significantly higher precision with reduced size, mass, 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 vehicle components such as heatshields. The higher quality data provided by NDL will enable both a more precise navigation towards the designated landing site and a well-controlled touchdown with greater stability and lower impact loads. Therefore, 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 planetary moons.

NDL transmits three laser beams at fixed but different pointing angles toward the ground to measure range and velocity along each beam using a frequency modulated continuous wave (FMCW) technique.[3] The three Line-Of-Sight (LOS) measurements are then combined in order to determine the three components of the vehicle velocity vector and its altitude relative to the ground. NDL can measure velocities up to 218 m/sec along the LOS of its beams from over 5 km altitude.

2. Spaceflight Engineering Test Unit

NDL's capabilities have been evaluated over the course of its development and maturation by conducting a series of helicopter and fixed-wing aircraft flight tests, a high-speed rocket-propelled sled test, and two test campaigns onboard autonomous rocket-powered test vehicles while operating in open and closed-loop with a guidance, navigation, and control (GN&C) system.[4-6] Results and lessons learned from these test campaigns helped the design and build of four spaceflight Engineering Test Units (ETUs): one for integrated ground and aircraft flight testing with landing vehicles' avionics, one for a suborbital flight test campaign, and two for lunar landing missions. Suborbital flights were conducted by Blue Origin onboard their New Shepard vehicle in 2020 and 2021. The two ETUs for lunar missions were recently delivered to the landing vehicle providers, Intuitive Machines and Astrobotic, for launch over coming months. NDL will help to both navigate these vehicles toward their intended landing locations and execute a well-controlled soft landing on the Moon surface. These lunar landing missions will serve as precursors for the development of fully certified spaceflight units for upcoming robotic and human landing missions.

Figure 1 shows one of the NDL ETUs consisting of an electro-optics chassis and an optical head. All the lidar components including the transmitter laser, receivers, and signal processor are housed in the electro-optics chassis. The optical head consists of three transmit/receive telescopes connected to the chassis via fiber optic cables. The chassis can essentially be installed anywhere on the vehicle, but the optical head must have a clear view of the ground.

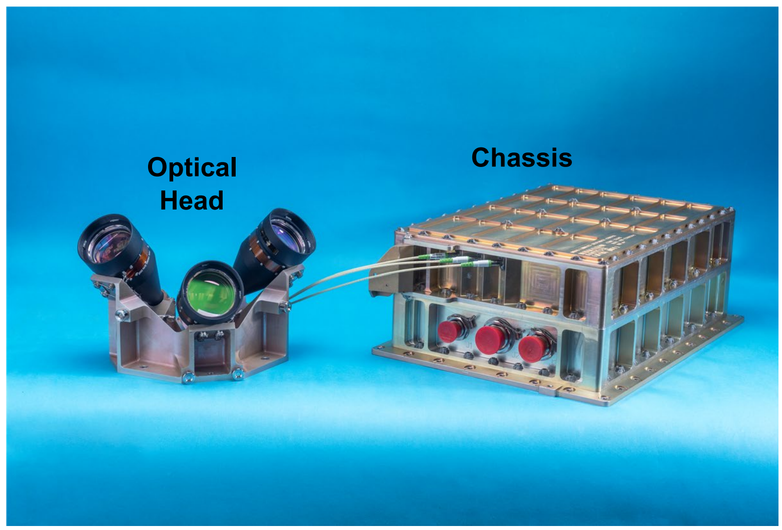

Figure 1. NDL Spaceflight Engineering Test Unit.

ETU components are mostly engineering models of space-grade parts. The remaining components are either Commercial-Off-The-Shelf (COTS) or custom-built parts that were subjected to selective component-level environmental testing, including vibration, shock, thermal/vacuum, and radiation as deemed necessary. Both the chassis and optical head were designed, build, assembled, and tested per NASA processes and standards for spaceflight hardware. Environmental tests, including vibration, shock, thermal/vacuum, and electromagnetic interference, were conducted on each ETU chassis and optical head before delivery to the commercial vehicle providers.

3. ETU Performance Characterization

The NDL ETU is capable of measuring velocity and range with 2 mm/sec and 12.5 cm precision, respectively, from over 10 km slanted range in a static environment. However, NDL's performance degrades in a dynamic operational environment during descent and landing. Therefore, a series of ground tests were devised to gather the necessary data for predicting ETU performance in relevant operational environments that includes vehicle dynamics, flight trajectory, surface albedo, and vacuum. The most comprehensive tests were a series of truck tests conducted at the Joint Base Langley-Eustis runway which provides a relatively long path length. For these tests, NDL is placed at one end of the runway pointing its beams toward a calibrated target on the back of a moving truck (see Figure 2). The target used for these measurements has a diffuse Lambertian surface and was placed nearly orthogonal to the NDL beams' optical axis. Range, velocity, and return signal magnitude data were collected continuously as the truck traveled from 600 m range to 3.8 km. These tests were conducted in different configurations: 1) NDL chassis and transmit/receive telescopes on stationary platforms, 2) chassis on a vibration table and telescopes on a stationary platform, 3) telescopes in a vacuum chamber and chassis on a stationary platform.

Figure 2. Comprehensive performance test of NDL ETUs in relevant operational environments (vibration and vacuum).

Figure 3 provides an example of truck test results showing signal intensity as a function of range. The lidar equation fit to measured data indicates a maximum operational range well over 10 km in a static configuration. In the presence of a vibration load the signal intensity degrades due to frequency spectral broadening of the laser output radiation which in turn broadens the heterodyne signal spectral. Broadening of signal spectral reduces peak signal power and increases error in signal frequency estimation. In fact, NDL's performance is dominated by the vehicle vibration limiting its maximum operational range and measurements precision. The results of Figure 3 show the maximum operational range reducing from over 10 km to about 7 km operating in an expected vibration load level for a lunar lander. In order to predict the lidar performance on the Moon, the lidar equation fit is adjusted for expected surface albedo and the effect of the atmosphere is taken out. These measurements are significantly affected by the atmospheric turbulence, absorption, and scattering since the laser beam is propagated horizontally at approximately 1.5 m above the runway's concrete surface. As a result, the maximum slant range of each beam is estimated to be over 6.5 km on the Moon. Precision was also measured as a function of range showing up to over an order of magnitude degradation at longer ranges. These performance parameters are still significantly better than radars and well within the acceptable regime of landing vehicles.

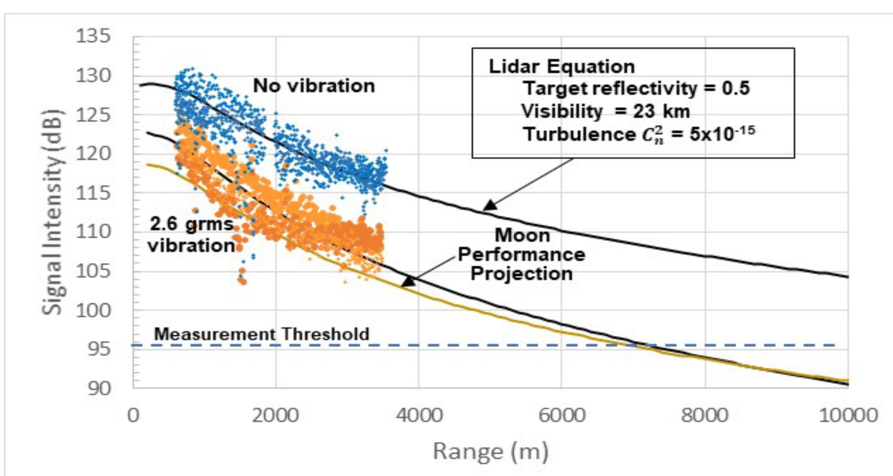

Figure 3. Estimated maximum operational range of NDL ETUs extrapolated from truck test data.

A test of NDL with the optical head in a vacuum chamber verified expected operation on the Moon as depicted in Figure 3. The focusing of the transmit/receive telescopes are adjusted for operation in vacuum before conducting the truck test with the telescopes in a vacuum chamber, thus little difference in signal intensity was observed when comparing the data with that of telescopes in atmospheric pressure.

4. Conclusion

NDL, developed at NASA Langley Research Center, is a viable alternative to radar sensors for providing onboard velocity and altitude data during descent and landing on planetary bodies. Two of the four NDL ETUs have been delivered for two separate landing missions that will be launched over coming months. These missions will demonstrate the NDL capabilities for future human and robotic landing missions to the Moon, Mars, and other planetary destinations.

In addition to conventional environmental testing for spaceflights, a series of performance characterization tests were conducted to predict the performance of the NDL ETUs in upcoming lunar landing missions. The vehicle vibration environment is identified as the dominant cause of NDL performance degradation limiting its maximum operational range and measurement precision. A comprehensive long-range truck test while the NDL system was being subjected to different vibration levels provided the necessary data for predicting the performance of the NDL ETUs on the upcoming lunar missions. These results indicate that NDL still meets the maximum operational range for upcoming landing missions and outperforms radar sensors by about an order of magnitude in precision. These characterization tests also identified areas of potential improvements for the next generation NDL including better vibration isolation of the laser source.

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