

# Development of Navigation Doppler Lidar for Future Landing Mission

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**A coherent Navigation Doppler Lidar (NDL) sensor has been developed under the Autonomous precision Landing and Hazard Avoidance Technology (ALHAT) project to support future NASA missions to planetary bodies. This lidar sensor provides accurate surface-relative altitude and vector velocity data during the descent phase that can be used by an autonomous Guidance, Navigation, and Control (GN&C) system to precisely navigate the vehicle from a few kilometers above the ground to a designated location and execute a controlled soft touchdown. The operation and performance of the NDL was demonstrated through closed-loop flights onboard the rocket-propelled Morpheus vehicle in 2014. In Morpheus flights, conducted at the NASA Kennedy Space Center, the NDL data was used by an autonomous GN&C system to navigate and land the vehicle precisely at the selected location surrounded by hazardous rocks and craters. Since then, development efforts for the NDL have shifted toward enhancing performance, optimizing design, and addressing spaceflight size and mass constraints and environmental and reliability requirements. The next generation NDL, with expanded operational envelope and significantly reduced size, will be demonstrated in 2017 through a new flight test campaign onboard a commercial rocket-propelled test vehicle.**

## I. Introduction

Past landing missions, including Surveyor, Apollo, Viking, Phoenix, and Mars Science Laboratory relied on radar technology for their altitude and velocity data.<sup>1,2</sup> Our laser-based Navigation Doppler Lidar (NDL) offers major benefits including lower mass and smaller size, higher precision and data rate, much lower false alarm rates, and packaging and integration flexibility. These attributes of the NDL can enhance the capabilities of space vehicles to execute precision navigation and controlled soft landing while reducing the engineering margins, cost, and risk associated with mission landing. The NDL begins its operation during the powered descent phase of a landing from an altitude of a few kilometers above the ground. The vehicle navigation computer processes the lidar data alongside other landing sensor measurements, such as the Inertial Measurement Unit (IMU), to significantly improve the vehicle three-dimensional position and velocity vector knowledge. The improved navigation knowledge with the lidar precision vector velocity data enables the Guidance, Navigation, and Control (GN&C) system to continuously update the vehicle trajectory and maneuver toward the landing site. At the same time, the lidar data are used to trigger the sequence of events that must be executed precisely in order to safely land the vehicle with minimum design margins and fuel reserve. These landing events may include ejection of parachutes and firing of reaction control system (RCS)

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thrusters. During the terminal descent phase, the highly reliable and accurate lidar data helps to control the vehicle horizontal and vertical velocities to within a few cm/s, which enables a well-controlled and soft touchdown. The capability to tightly control touchdown (i.e., minimize lateral velocity and tightly govern vertical velocity) translates to greater stability and lower impact loads to the vehicle, which can result in simplification and mass savings to the landing gear structure and likely lower fuel reserves. Therefore, incorporation of the NDL into the landing GN&C system 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.

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 used to derive the three components of the vehicle velocity vector, and its altitude and attitude relative to the ground below.<sup>3,4</sup> A prototype version of NDL was built under the ALHAT (Autonomous Landing and Hazard Avoidance Technology) project and demonstrated through a series of flight tests onboard a rocket-powered free-flyer vehicle (Morpheus).<sup>5,6</sup> Operating in closed-loop with the vehicle's GN&C system, the NDL data was used to land precisely at a safe location surrounded by hazardous rock piles and craters. This paper describes the NDL design and capabilities as demonstrated by the closed-loop Morpheus flight tests, as well as the ongoing activities for NDL performance envelope expansion and technology maturation towards a spaceflight qualified instrument.

## II. NDL Sensor System Description

Figure 1 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 microns is used as the master oscillator. The frequency of this laser is modulated linearly in time. The master oscillator laser power is amplified for transmission while a portion of the power is used as the local oscillator (LO) in an optical homodyne detection configuration. The lidar transmits laser beams through collimating lenses into three different directions relative to each other, and the return signals from each beam are collected by the same lenses and directed to three corresponding photo-receivers. The digitized outputs of the photo-receivers are processed by a Fast Fourier Transform (FFT) algorithm that extracts LOS velocity and range measurements. The platform velocity vector is obtained from the LOS velocity measurements, given a priori pointing knowledge. Three simultaneous LOS range measurements provide vehicle altitude relative to the local ground without the need of vehicle attitude angle data from a separate sensor. 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.<sup>4</sup> Figure 2 shows the prototype NDL, we refer to as the 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.

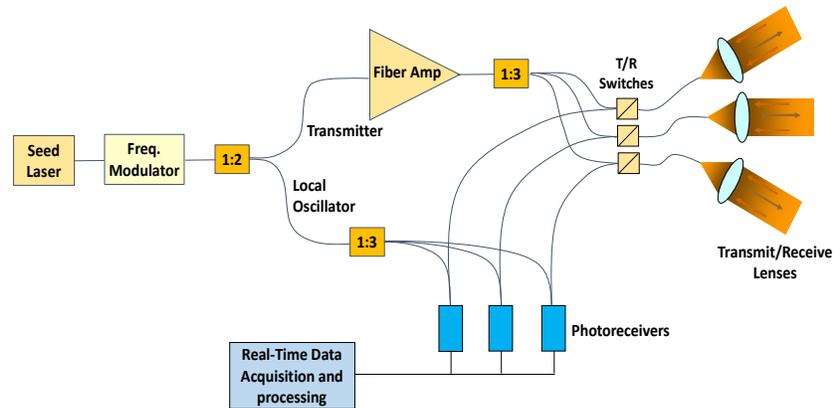


Figure 1. Navigation Doppler Lidar system diagram.

## III. Flight Tests and Results

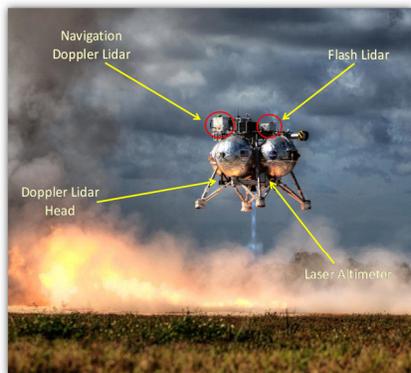
The capabilities of the Doppler lidar were evaluated and its performance characterized during different stages of its development. Extensive laboratory experiments and dynamic field tests were made by different means including a

swinging platform from the NASA LaRC gantry (a 240-foot high structure), a moving truck, and three helicopter flight test campaigns.<sup>7-9</sup> These tests helped the development of the GEN 2 prototype unit and functional demonstration onboard a rocket-propelled Vertical Testbed (VTB) referred to as Morpheus (Fig. 3).<sup>10,11</sup> The flight tests also included a 3-D imaging flash lidar and a long range laser altimeter that we developed under the ALHAT project along with the NDL.<sup>3,12,13</sup>

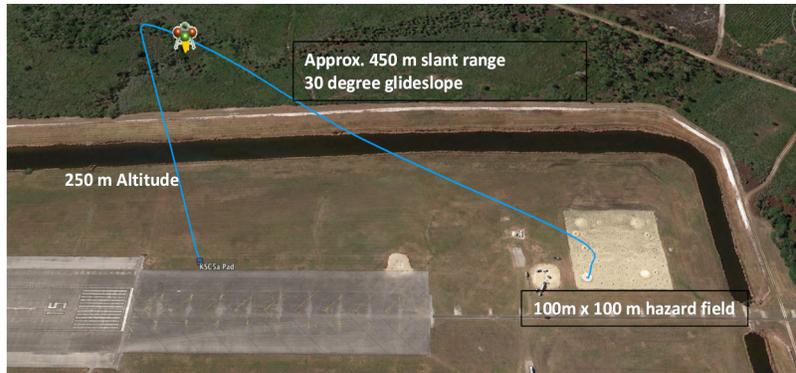
The demonstration flights were conducted in 2014 at the NASA Kennedy Space Center Shuttle Landing Facility. A 100 m x 100 m hazard field was constructed specifically for these flights, simulating a challenging lunar terrain complete with realistic hazard features (rock piles and craters) and designated landing areas.<sup>14</sup> The Morpheus flight test campaign began with three open-loop flights for assessing the lidar sensors and the ALHAT Navigation system followed by three closed-loop flights for full demonstration of the ALHAT landing system. During the open-loop flights, the Morpheus GN&C used the data in a navigation system called Vertical Test-Bed (VTB) Nav, to execute pre-defined trajectory profiles and land on a specified location within the hazard field. The VTB Nav determined the vehicle's position and velocity vector from the measurements provided by a GPS sensor, a high-grade Inertial Measurement unit (IMU), and a commercial altimeter.<sup>10</sup> In the latter three flights, the ALHAT Navigation system took over, operating in closed-loop with the Morpheus GN&C to autonomously, and without the use of GPS data, land safely on the hazard field. The Hazard Detection System (HDS) used 3-D image frames generated by the flash lidar to create an elevation map of the hazard field, identify the best safe landing site, and report the coordinates of the selected site to the vehicle GN&C system.<sup>15</sup> The data from the NDL was then used by the GN&C system to navigate and land the vehicle precisely at the selected location, while avoiding hazardous rocks and craters that were previously identified from the flash lidar images (Fig. 3b).<sup>10</sup>



**Figure 2. Prototype (GEN 2) Navigation Doppler Lidar system including the electronic chassis and an optical head.**



(a)



(b)

**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.**

Figure 4 provides the NDL data from the last Morpheus flight showing the velocity vector magnitude and the altitude derived from the three simultaneous LOS velocity and range measurements. There are a few instances of data dropouts at the beginning of the flight and at 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 Navigation system was designed to dead-reckon to a soft landing by utilizing the precision velocity vector provided by the NDL prior to the creation of dust plume during the final stage of descent.

Figure 6 provides the individual LOS velocity and range data measured by each beam. From these measurements, the velocity vector and attitude-independent altitude shown in Fig. 4 is computed. Figure 6a compares the NDL LOS velocity (red curves) with the VTB Nav velocity projected along the lidar beams (blue curves). These plots illustrate the excellent agreement between NDL measurements and the navigation state solutions which were obtained independently from GPS, IMU, and altimeter sensors. Figure 6b provides the three LOS measurements of range to ground. One of the beams (blue curve) looks along the flight path and measures 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 NDL velocity and range precision, defined as random noise about their mean, are 1.7 cm/sec and 2.2 m 1-sigma, respectively. The measurement noise is dominated by the vehicle vibration, acceleration and angular velocity during the signal acquisition time of about 1 msec. The NDL velocity and altitude precision demonstrated in the Morpheus flights are more than an order of magnitude better than state-of-the-art radars, enabling a wide range of precision and well-controlled descent and landing maneuvers.

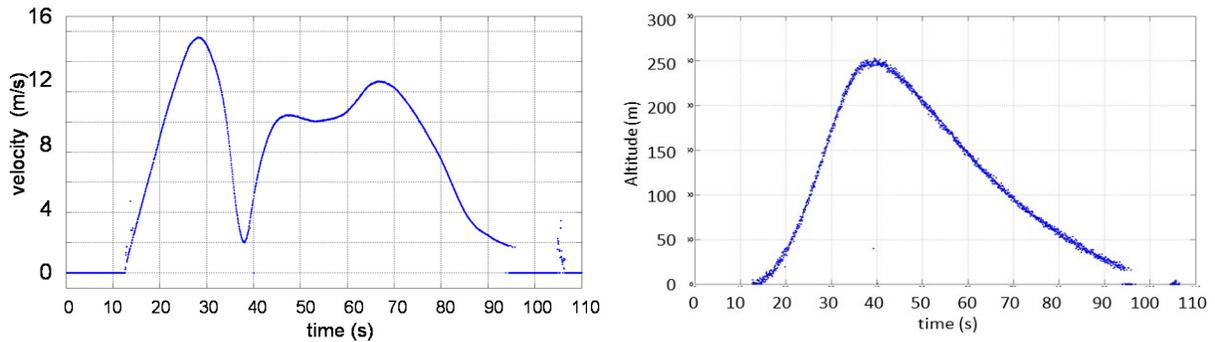


Figure 4. Morpheus flight test data: LOS velocity (left) and range (right).



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

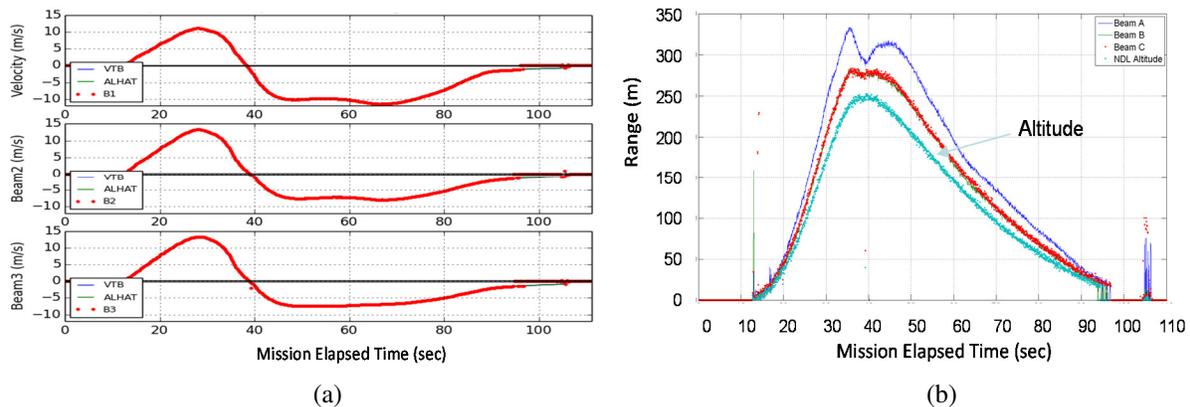


Figure 6. NDL LOS velocity (a) and range (b) measurements for each of the three beams.

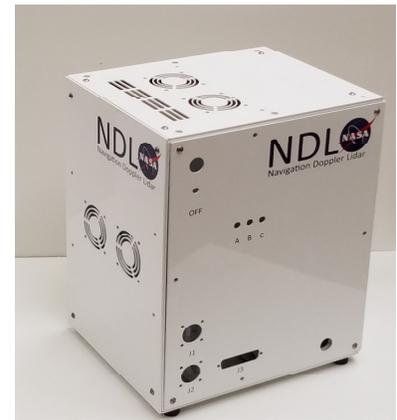
#### IV. Design Upgrades and Performance Enhancement

After successful Morpheus flight demonstrations, our focus shifted to optimize the prototype system design and to address space qualification requirements. The GEN 3 NDL currently under development extends the NDL operational envelope, increasing its maximum velocity from 70 m/s to 200 m/s and maximum range from 2.5 km to over 4 km. The operational enhancements were implemented in order to expand the utilization of the NDL supporting different missions with varying descent and landing maneuvers. The design upgrades being incorporated in the GEN 3 NDL will also result in about 40% reduction in size and mass compared with the GEN 2 instrument. The GEN 3 sensor, shown in Fig. 7, is intended to have the same form factor of a spaceflight unit. Table 1 summarizes the performance and physical specifications of the GEN 3 NDL and compares them to the GEN 2 system demonstrated through helicopter and Morpheus flight tests.

**Table 1. GEN 2 and GEN 3 NDL Specifications.**

Parameter		GEN 2	GEN 3
LOS Velocity Error <sup>a</sup>		0.2 cm/sec	0.2 cm/sec
LOS Range Error <sup>a</sup>		30 cm	30 cm
Maximum LOS Range		2500 m	4000 m
Data Rate		20 Hz	20 Hz
Dimensions	Electronic Chassis	44 x 38 x 16 cm	29 x 23 x 20 cm
	Optical Head	34 x 33 x 21 cm	34 x 33 x 21 cm
Mass	Electronic Chassis	16.4 kg	10 kg
	Optical Head	5.2 kg	5 kg
Power (28 VDC)		95 W	90 W

a. Errors do not include platform contributions (vibration and angular motions)



**Figure 7. GEN 3 NDL electronic chassis currently under development.**

The GEN 3 system will be completed in the summer of 2016. The next planned operational tests integrate the NDL with JPL's Landing Vision System (LVS)<sup>16,17</sup> and navigation system and conduct a flight test onboard a rocket-powered free-flyer vehicle built by Masten Space Systems. The LVS is capable of drastically reducing the vehicle position knowledge error by comparing visible images of the terrain with an onboard map. The integrated NDL, LVS and avionics system is referred to as COBALT (CoOperative Blending of Autonomous Landing Technologies). The ability of the LVS to provide accurate position data during the descent phase combined with the NDL's precise surface-relative velocity vector and altitude data present a complete precision landing solution. The vehicle will be able to initiate a divert trajectory optimized for fuel efficiency from several kilometers down range towards the designated landing site and perform a safe and tightly-controlled terminal descent and landing maneuver. NASA Johnson Space Center has the system engineering and project management responsibilities for COBALT integration and flight testing. The Masten vehicle, designated as Xodiac, selected for the flight test is considerably smaller and has a lower payload capacity than Morpheus, but can ascend to higher altitudes. This flight test campaign, scheduled for early spring 2017, will demonstrate the NDL upgrades and performance enhancements implemented since the Morpheus flights.

#### V. Technology Maturation for Spaceflights

The Morpheus flight test campaign demonstrated reliable NDL operation as an integrated sensor of the GN&C system. The Morpheus flights also provided valuable experience for integration of this new sensor into landing vehicles and the use of its data for executing precision descent maneuvers and well-controlled landing.<sup>18</sup> The upcoming flights aboard the Xodiac vehicle will demonstrate the NDL's operation with a different set of avionics and navigation filter over a Mars-like descent trajectory as opposed to a lunar trajectory exercised by the Morpheus vehicle.

The Morpheus and Xodiac flight tests serve as an excellent demonstration of the NDL in a relevant operational environment. A parallel effort is devoted to addressing the NDL operation in a space environment. Supported by

NASA's New Frontier program, the key laser subsystem of the NDL is being re-engineered to meet the stringent spaceflight qualification requirements. The laser subsystem consisting of a highly stable single-frequency seed laser and a single-mode fiber amplifier will be tested in the NDL system. A copy of the GEN 3 unit that includes spaceflight-qualifiable components will be assembled to serve as a testbed and engineering model for the development of the GEN 4 NDL, commonly referred to as the Engineering Test Unit (ETU). The ETU is essentially a pre-spaceflight unit subjected to extensive spaceflight-qualification and reliability testing. The spaceflight-qualifiable seed laser and fiber amplifier will be integrated into the GEN 3 NDL in early 2017. The remaining components and subsystems will be replaced by their space-qualifiable versions as they are built or procured over time.

## VI. Conclusion

The Navigation Doppler Lidar is expected to play a critical role in NASA's future planetary exploration missions. It will provide the necessary data for precision navigation and executing well-controlled landings on solar system bodies. Compared to radars, the NDL offers over an order of magnitude higher precision velocity and altitude measurements without ambiguities or target clutter while significantly reducing the required mass, size, and power. The viability of this technology for future missions was successfully demonstrated onboard the Morpheus rocket-propelled free-flyer vehicle built by NASA Johnson Space Center. The GEN 3 NDL currently under development extends the NDL operational envelope, increasing its maximum velocity from 70 m/s to 200 m/s and maximum range from 2.5 km to over 4 km. With these operational enhancements the NDL can support different missions requiring varying descent and landing maneuvers. The design upgrades being incorporated in GEN 3 NDL will also result in about 40% reduction in size and mass compared with the GEN 2 instrument to comply with the constraints of landing vehicles. The next generation NDL will be demonstrated in early 2017 as an integrated subsystem of COBALT payload that includes JPL's Lander Vision System and navigation filter. Additionally, an effort is underway for reducing the technical risks associated with the development of a spaceflight unit. A spaceflight-qualifiable version of the NDL's key laser subsystem is being built and the spaceflight qualification of its other components are being studied. We expect to integrate the space-grade or space-qualifiable components into an Engineering Test Unit (ETU) in time for landing missions being considered for launch in the early 2020s.

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