Navigation Doppler Lidar Performance at High Speed and Long Range

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NASA is developing a Navigational Doppler LiDAR (NDL) for use in missions involving robotic and human landing scenarios on solar system bodies. The NDL provides unprecedented accuracy in position and velocity measurement for the guidance, navigation and control (GNC) subsystem of a spacecraft. NDL performance has been characterized over different phases of its development through ground tests, helicopter flight tests, and onboard rocket-powered test vehicles, however, none of these tests provided measurements over its full performance envelope. For this reason, a high speed rocket sled test was recently conducted to resolve both range and velocity up to the maximum limits of the NDL. This test campaign was performed at the Supersonic Naval Ordnance Research Tracks (SNORT) facility, Naval Air Weapons Station China Lake, as part of the Safe & Precise Landing and Integrated Capabilities Evolution (SPLICE) project.

I. Introduction

Past landing missions relied on radar technology for altitude and velocity data.[1,2] Laser-based Navigation Doppler Lidar (NDL)[3] 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 several kilometers altitude above the ground. The NDL transmits three beams at fixed but different directions, each measuring both range and velocity at 20 Hz. The three simultaneous line-of-sight (LOS) measurements are then used to determine the vehicle vector velocity and altitude relative to the local ground. The resolutions of LOS velocity and range measurements are 0.2 cm/sec and 25 cm. Each beam is expected to reach at least 4000 m in range, depending on atmospheric conditions and ground albedo, and up to 218 m/s in velocity.

The capabilities of the Doppler lidar were evaluated and its performance characterized through ground tests, helicopter flight tests, and onboard autonomous rocket-powered test vehicles while operating in open and closed-loop with a guidance, navigation, and control (GNC) system.[4-6] However, the previous tests were limited in either operational range or velocity or both. Therefore, a test campaign at China Lake SNORT facility was devised to measure the NDL performance over its full operational limits. The China Lake SNORT facility is capable of

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generating high-speed testing that allows systems to be evaluated under controlled, dynamic conditions. The SNORT facility uses solid rocket-propelled sleds on a very straight 6.6 km long monorail to generate high speeds. The desired speed profiles are achieved by selection of rockets with different thrust levels and precisely timing their ignition.

For this test campaign, a small retroreflector and a diffuse target about 1 m by 1 m in dimensions were used as a target on the sled (Fig. 1). The NDL's telescopes were setup at one end of the track, as shown in Fig. 2, such that at least one of the three beams is centered on the target at any given time over the course of the test as the sled travels from the far end of the track towards the NDL. A test speed profile was designed to reach a maximum speed of approximately 230 m/s at 4 and 2 km distances from the NDL. This test speed profile ensures that the sled travels at speeds around 200 m/s for a considerable period of time at ranges 3.9-4.2 km, and at least once exceeds the NDL maximum speed capability of 218 m/s.

Fig. 1 Rocket sled with a diffuse target and a small retroreflector.

Fig. 2 NDL and its three transmit/receive telescopes placed on the end of the rocket-sled track.

The laser beam pointing was severely impacted by strong atmospheric turbulence present in the summer desert climate. The atmospheric turbulence causes significant beam wander over long propagation distances of up to 4.2 km. At such path lengths over a horizontal path of approximately 1.5 meters above the ground, the NDL laser beam can randomly wander over a circle several meters in diameter. For some test runs when the atmospheric condition was more favorable (e.g., before sunrise), the telescopes pointing could be aligned such that all three beams remained on the target over the full course of the sled travel.

The tests were performed under various atmospheric conditions and the relevant parameters, including wind speed and direction, humidity, and pressure were recorded. A scintillometer was used to measure path-averaged turbulence strength over the laser propagation path. These atmospheric data are used to analyze the performance of the NDL and to estimate its maximum range under different operational scenarios in terrestrial and planetary environments.

II. High speed performance

The sled test at SNORT provided objective data of the NDL's performance over its full velocity range from less than 1 cm/s to 218 m/s at distances greater than 4 km. The sled track is very straight, and runs north along the China lake test site. Survey data provided by China Lake personnel shows the track east-west deviation is less than 13 cm from a straight path over the entire track, but, the track elevation drops about 34 m (Fig. 3) from one end to the other. The change in elevation made it difficult to track the sled with the NDL laser beam over the entire 4.2 km range. The tacking of the sled with the laser beam became essentially impossible in the presence of daytime atmospheric turbulence. Therefore, the three telescopes were carefully aimed such that at least one of the telescope could detect the sled as it travels along the track. For ranges under 2 km the elevation change and the turbulence-induced beam wander are small enough that all three telescopes could detect the sled.

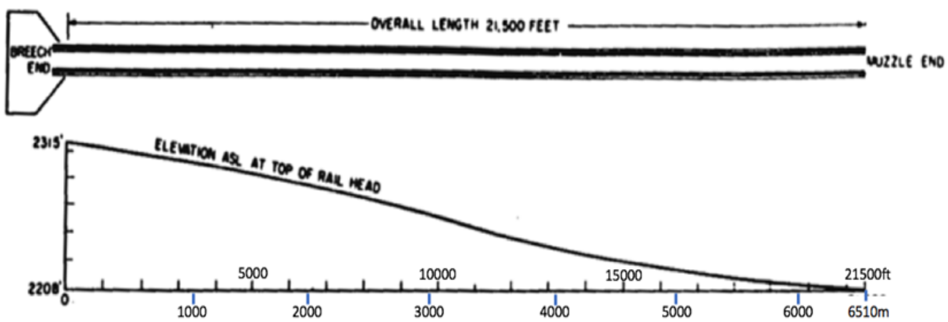

Fig. 3 SNORT track range and elevation drop. A total of eight test runs were planned, four at 4 km and four at 2 km.

The atmospheric turbulence was measured by an optical scintillometer during each test run. Fig. 4 shows the index of refraction structure constant which is related to the strength of atmospheric turbulence over the course of the test days. The atmospheric turbulence strength is relatively low or moderate before sunrise, then decreases to a minimum level just before and during sunrise before rapidly increasing as the sun warms the earth. This is a typical profile for most parts of the year in deserts. Therefore, it is best to align the laser beams and conduct the tests before sunrise in order to minimize the impact of the turbulence-induced laser beam wander. However, this proved difficult due to the required preparations and the logistics at the SNORT facility.

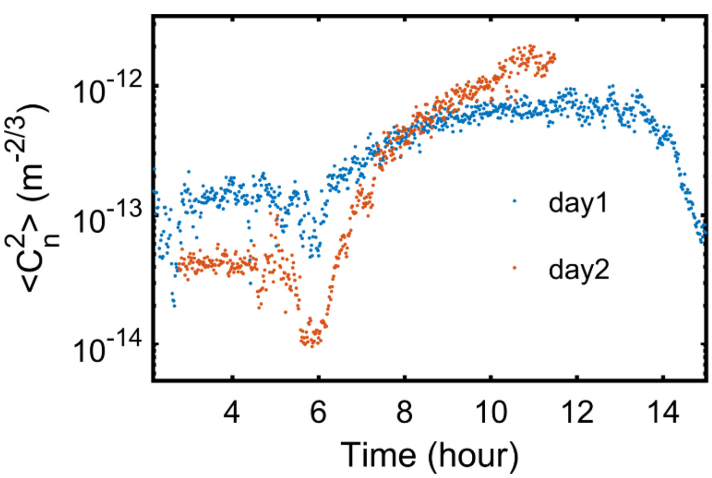

Fig. 4 Time series of optical turbulence during two days of testing.

Examples of the velocity and range measurements for 2 and 4 km ranges are shown in Fig. 5. In both cases, the sled maintained speeds above 200 m/s for about 4 seconds. The NDL provided valid measurements in both cases over the entire range and speed profile. These plots show greater numbers of data dropouts at longer distances, which can be attributed to the turbulence-induced beam wander.

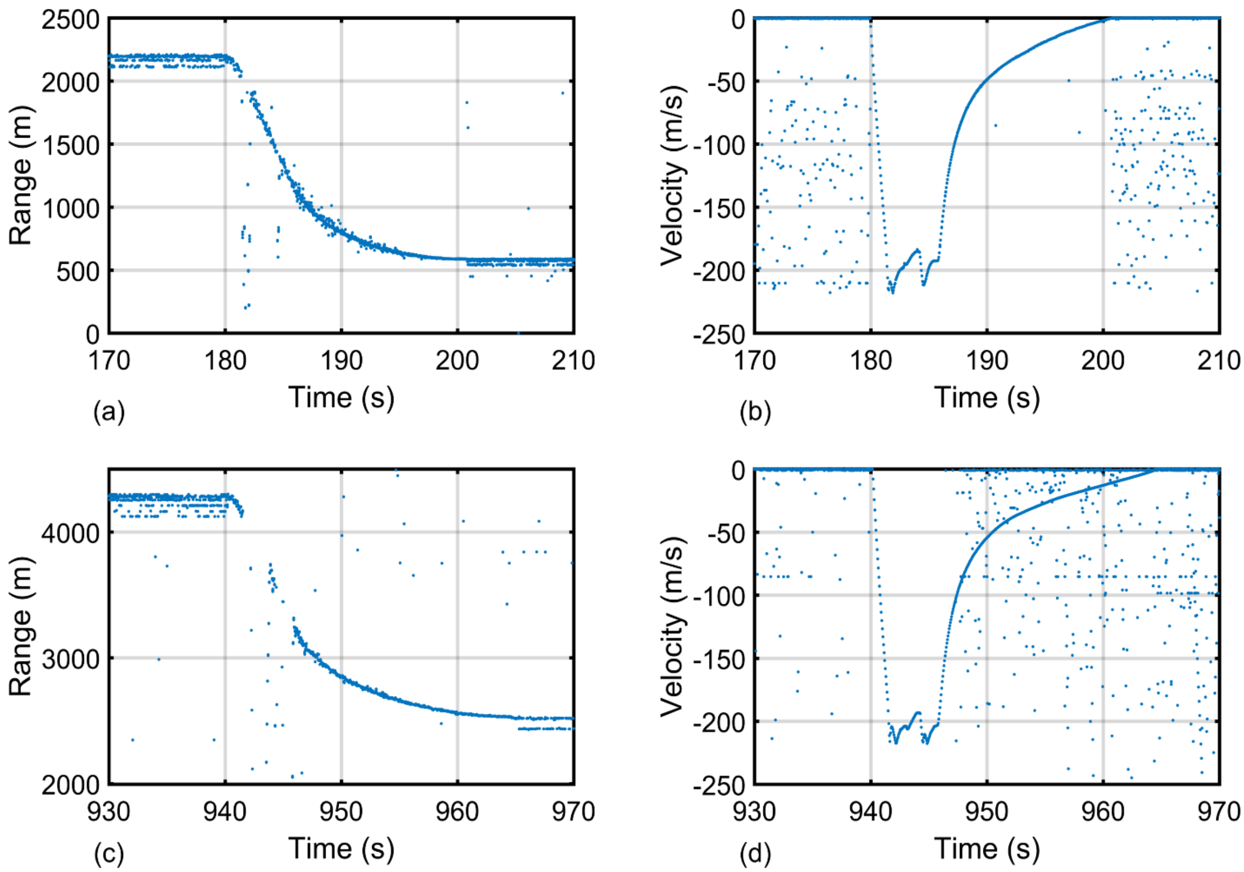

Fig. 5 Range (a and c) and velocity (b and d) measurements, 2 km (top row) and 4 km (bottom row).

Figures 6 and 7 compare the NDL measurements with the data provided by the SNORT's high-speed video monitoring system (VMS) and Doppler radar instrument. These plots show excellent agreement between the NDL and the SNORT's instruments. The radar measurements deviate from the NDL at velocities lower than 210 m/s but closely follow the NDL results at 4 km and at speeds exceeding 200 m/s. This deviation may be attributed to intrinsic radar measurement noise and bias errors.

As the sled velocity exceeds the NDL maximum velocity of 218 m/s, the signal frequencies alias and can be converted in post processing. The inset plots of Figure 6 show the application of an anti-aliasing algorithm. This provides an opportunity to extend the operational envelope of the NDL if required by the landing vehicle. However, 218 m/s of line-of-sight (LOS) velocity seems sufficient for almost all descent and landing scenarios.

The analysis of the NDL data and comparative study with the SNORT's VMS and Doppler radar data is still ongoing. The NDL data rate of 20 Hz and velocity and range measurement resolutions of 0.2 cm/s and 25 cm, respectively, are greater than the data provided by the SNORT instrumentation. As a result, the comparative data analysis is not trivial and requires careful interpolation of the NDL data to match the timing of the SNORT's data.

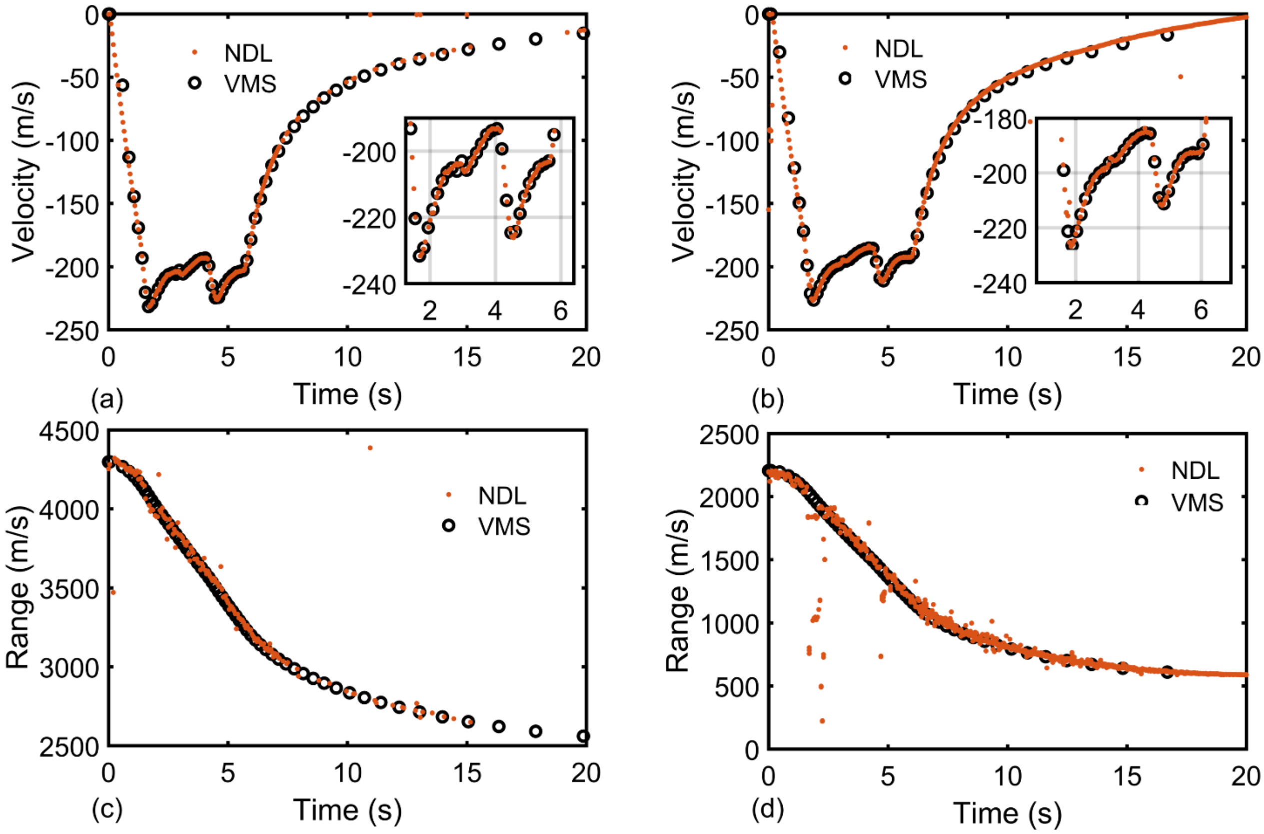

Fig. 6 Range (a and c) and velocity (b and d) measurements at 2 and 4km. NDL compared to SNORT video monitoring system.

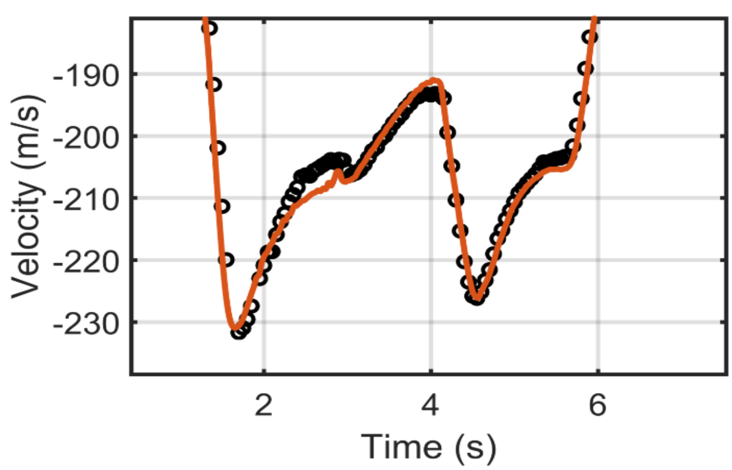

Fig. 7 NDL vs. Radar velocity measurements and residuals.

III. Conclusion

The performance of the Navigation Doppler Lidar over its full operational envelope (maximum velocity at long ranges) was verified through a test campaign at the China Lake SNORT facility. For this test, a known target was installed on a rocket-propelled sled traveling at high speeds on a monorail track. The NDL range and velocity measurements were compared to those provided by a Doppler radar and a video monitoring system and showed very good agreement. Despite beam pointing challenges caused by strong atmospheric turbulence of the warm desert summer, the SNORT facility proved to be an excellent facility for testing the NDL over long ranges and at high speeds.

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