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Fiber Doppler Lidar for Precision Navigation of Space Vehicles

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ABSTRACT: A fiber-based coherent Doppler lidar capable of providing highly accurate vector velocity and altitude data has been developed for precision navigation of space vehicles landing on the Moon, Mars, or asteroids.

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1. Introduction

Precision navigation to the designated landing site on the surface of the Moon or Mars, formation flying or landing on asteroids, and rendezvous and docking with orbiting spacecraft or space station, all require accurate knowledge of the vehicle relative velocity and altitude [1-4]. For example, future landing missions may require landing within a few meters of pre-deployed assets or landing in a small area surrounded by rocks, craters, or steep slopes [5-7]. To meet this requirement, a Doppler lidar is being developed by NASA under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project [8,9]. The range and velocity measurements provided by this lidar sensor will be used by an autonomous Guidance, Navigation, and Control (GN&C) system to accurately navigate the vehicle to the designated landing location.

As a landing sensor, the Doppler lidar will begin its operation during the powered descent phase from an altitude of a few kilometers above the ground. The GN&C system processes the lidar data to improve position and attitude data from the Inertial Measurement Unit (IMU). The improved position and attitude knowledge along with the lidar precision vector velocity data enable 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 important role in performing the soft landing maneuver. For example, large robotic or manned vehicles must control their horizontal and vertical velocities to better than 0.5 m/s in order to avoid the risk of tipping over and ensure a gentle touchdown. To control to these limits will require measurement accuracies to better than 10 cm/s. The coherent Doppler lidar, being described in this paper, exceeds these requirements by over an order of magnitude.

2. System Description

The Doppler lidar obtains high-resolution range and velocity information from a frequency modulated continuous wave (FMCW) waveform for which the laser frequency is modulated linearly with time. Figure 1 shows the transmitted laser waveform and the retuned waveform from the target delayed by ta, the light round trip time. When mixing the two waveforms at the detector, an interference signal will be generated whose frequency is equal to the difference between the transmitted and received frequencies. This intermediate frequency (IF) is directly proportional to the target range. When the target or the Lidar platform is not stationary during the beam round trip time, the signal frequency will be also shifted due to the Doppler effect. Therefore by measuring the frequency during “up chirp” and “down chirp” periods of the laser waveform, both the target range and velocity can be determined. The difference in up-ramp and down-ramp frequency provides the vehicle velocity and their mean value provides the range to the target.

Figure 2 illustrates the system design concept 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 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 three LOS measurements are then combined in order to determine the three components of the vehicle velocity vector, and to accurately measure altitude and attitude relative to the local ground. The 45 degrees separation between the transmitted beams was chosen as a compromise between horizontal velocity accuracy that favors large angles, and higher operational altitude that is inversely proportional to the beam nadir pointing angle.

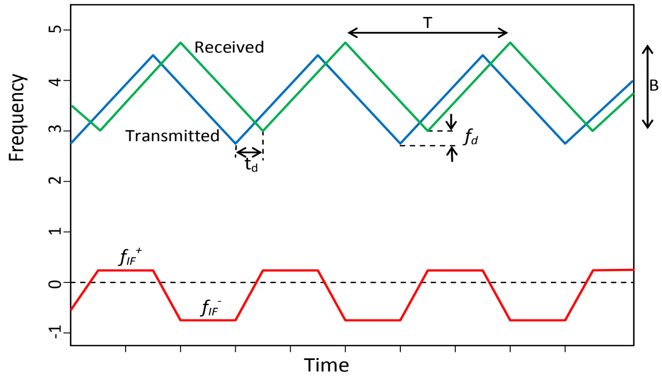

Fig 1. Laser frequency is linearly modulated to create a sawtooth waveform. Returned waveform from the target is delayed in time. In presence of platform or target velocity, the returned waveform will be Doppler shifted. The difference frequency (lower trace) obtained by homodyning the laser and returned beams contains both range and velocity information.

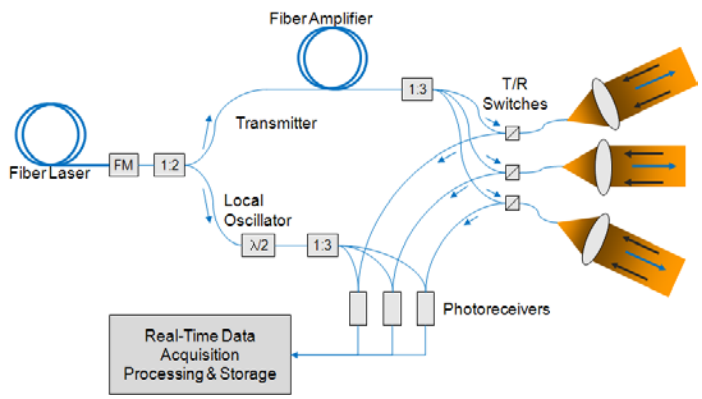

Fig. 2. Doppler lidar system configuration illustrating three transmitted beams and their corresponding receivers providing line-of-sight velocity and range measurements in three different directions.

The main factors determining the precision of the Doppler lidar measurement are the spectral linewidth of laser, the linearity of the modulation waveform, the signal-to-noise ratio, and the signal processor frequency resolution [8,9]. Fortunately, the advances in single-frequency fiber laser, high quantum efficiency detector, high-speed analog electronics, and powerful processor technologies have enabled the development a system with sufficient precision and operational range for a number of applications including planetary landing.

3. System Development and Tests

The capabilities of the Doppler lidar were evaluated and its performance characterized through two helicopter flight test campaigns. These campaigns were facilitated by NASA Jet Propulsion Laboratory (JPL), and were held at NASA Dryden Flight Research Center in California in 2008 and 2010 over vegetation-free terrain [10,11]. A prototype version of the Doppler lidar has recently been completed for a series of demonstration flight tests. As shown in Figure 4, the system consists of an electronics chassis and an optical head. The optical head will be mounted rigidly on the vehicle with a clear field-of-view to the ground, and connected by an armored fiber cable to the Doppler lidar electronics chassis. It is planned to demonstrate the viability of this lidar sensor system for future landing missions through a series of flight tests onboard a rocket-powered terrestrial free-flyer vehicle in 2012. The test vehicle, referred to as Morpheus, is being developed by NASA-JSC to demonstrate advanced propulsion and GN&C technologies for future landing missions. The lidar will be operating in a closed-loop with a GN&C system controlling the vehicle flight trajectory and soft landing at the selected safe site.

4. References

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