Coherent Doppler Lidar for Precision Navigation of Spacecrafts

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1. Introduction

Future robotic and manned exploration missions to the Moon, Mars, and other planetary bodies will require precision navigation to the identified safe landing sites. The designated landing sites may include areas of high scientific value with relatively rough terrain or areas near pre-deployed assets demanding a landing accuracy of the order of a meter[1]. To meet this stringent requirement, a Doppler lidar is being developed by NASA under the Autonomous Landing and Hazard Avoidance (ALHAT) project. This lidar sensor is a versatile instrument capable of providing precision velocity vectors relative to the sensor reference frame, vehicle platform altitude, and ground relative attitude. This allows the vehicle to accurately navigate from a few kilometers altitude to the identified safe landing location to within a meter. The identification of the safe landing location is performed by a 3-D Imaging Flash lidar that is being developed in parallel[2].

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 t_a, 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.

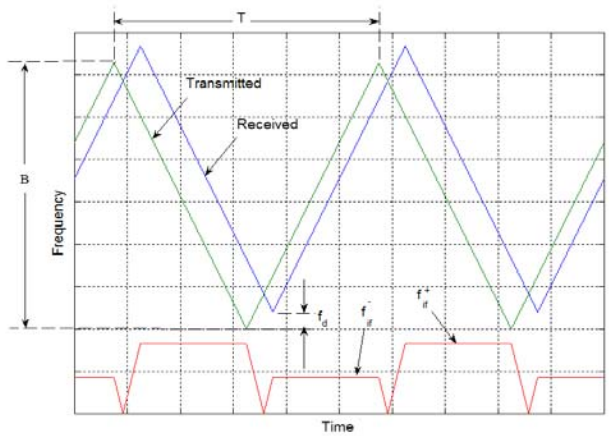

Fig. 1. Laser frequency is linearly modulated to create a sawtooth waveform. Returned waveform from the target is delayed in time. In presence of platform or target velocity, the returned waveform will be Doppler shifted. The difference frequency (lower trace) obtained by homodyning the laser and returned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

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 receiver.
The LO optical field mixes with the time delayed received field at the detector yielding a time varying intermediate frequency (IF) as shown by

the lower trace in Figure 1. By extracting the up-ramp and down-ramp frequencies, the platform velocity and range to the ground along the laser line-of-sight (LOS) can be determined. The lidar transmits 3 laser beams separated 45 degrees pointed nadir in order to determine the 3 components of the vehicle velocity, and to accurately measure altitude and attitude relative to the local ground.

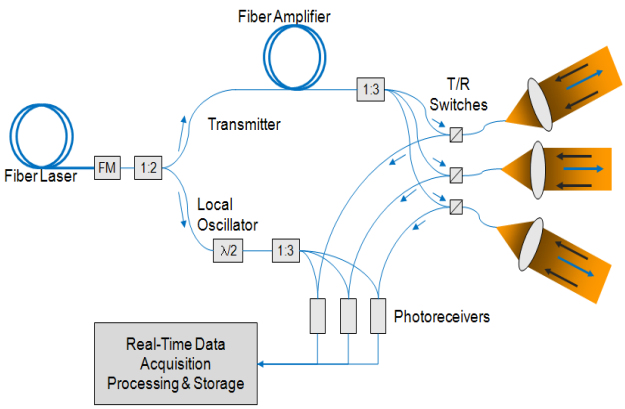

Fig. 2. Doppler Lidar system configuration illustrating 3 transmitted beams and their corresponding receivers providing line-of-site velocity and range measurements in 3 different directions.

3. System Development and Tests

Previously, a breadboard Doppler Lidar was assembled and tested onboard a helicopter in 2008 to evaluate its capabilities for the landing application. This test was conducted at NASA Dryden in California over a vegetation-free terrain[3]. That test campaign consisted of several passes with a figure 8 pattern over both flat and rough terrains. The lidar head was mounted in a gimbal looking nadir during each pass. The maximum altitude of this test was limited by the helicopter operational ceiling of about 1245 meters above the ground. Figures 3 and 4 provide examples of the lidar test data showing the helicopter velocity and altitude. Figure 3 compares the velocity magnitude measured by the lidar with the numerically derived velocity from the data collected by a GPS receiver. The expanded view of a portion of the data shows the raw GPS velocity data, the post processed GPS data, and the Doppler lidar velocity measurements. There is an offset of about 10 cm/sec between the lidar measurements and the post-processed GPS data that may be attributed to a bias error in GPS data. The error in numerically derived GPS velocity data is estimated to be less than 3 cm/sec, but its bias error is not clearly understood. The Doppler lidar data shows spikes in velocity several times during each flight. These spikes are caused by the motion of the gimbal when going from locked nadir position to a stowed position at the end of each pass over the terrain. These velocity spikes are not detected by the GPS receiver since the GPS only tracks the helicopter motion.

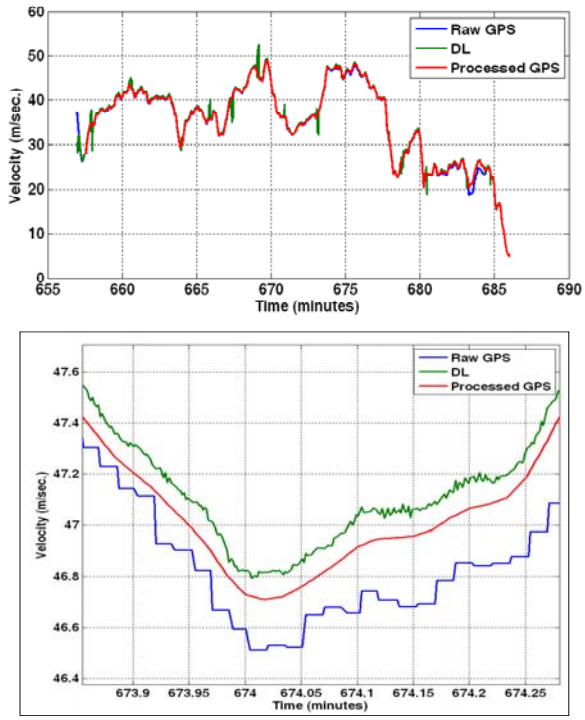

Fig. 3. Doppler lidar velocity measurement compared with GPS data. Lower plot shows an expanded portion of data showing discrepancy between the Doppler Lidar and GPS data.

Doppler lidar uses all 3 LOS range measurements to determine the vehicle altitude. The use of all 3 beams allows for an accurate measurement of the vehicle altitude relative to the local ground that is reasonably insensitive to the terrain features such as boulders and slopes and is independent of the lidar nadir angle. Figure 4 is a plot of the helicopter altitude obtained by the Doppler lidar compared with the GPS altitude data. Since GPS provides altitude data relative to the global sea level, a nominal ground level is used to obtain a best fit of the two data sets. The difference between the lidar and GPS data, as shown in Figure 4, is essentially the ground elevation profile.

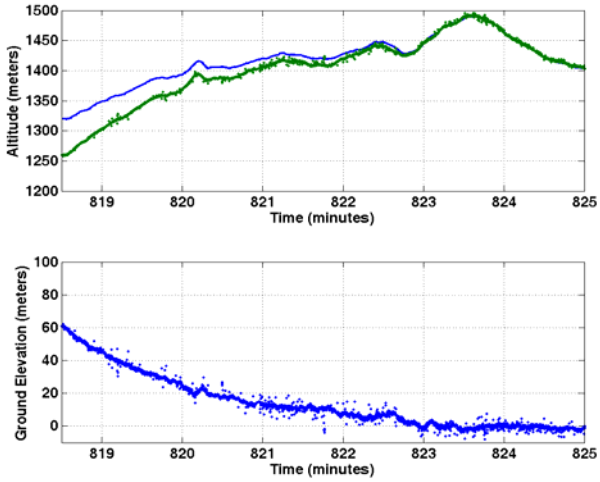

Fig. 4 Doppler lidar altitude measurement relative to ground compared with GPS altitude data relative to global sea level after subtracting a nominal ground level. The lower trace shows the difference between the two measurements that corresponds to the local ground elevation profile.

The data collected during the flight tests proved to be very valuable for the development of a compact and efficient prototype system shown in Figure 5. The characterization of the prototype system at the Lidar Static Test Range at NASA-LaRC revealed improved measurement precision of about 1 mm/sec in LOS velocity and 5 cm in LOS range.

Fig 5. Prototype Doppler lidar system tested from a helicopter platform indicating high accuracy velocity and range measurements capability exceeding the requirements for precision soft landing on planetary bodies.

The prototype system was then tested dynamically through another helicopter flight test campaign in summer of 2010. Examples of this flight test data are provided in Figures 6 and 7 where the Doppler Lidar data is compared with the data from a high-grade Inertial Measurement Unit (IMU) and GPS system built by Applanix. The Doppler Lidar data shows excellent agreement with the IMU/GPS data. With the scale of these plots, the Doppler Lidar and IMU/GPS data essentially overlap and are not distinguishable. The mean value of discrepancy in magnitude of the vector velocity measurements was about 3.5 cm/sec. As explained above, quantifying the discrepancies between the Doppler Lidar and IMU/GPS measurements of altitude is not as straight forward since one measures altitude with respect to the ground and the other relative to sea level. For the altitude plot of Figure 7, a fixed bias was subtracted from the GPS data so it could be compared with the above ground level (AGL) altitude measurements of the Lidar. This ground altitude bias was determined from the Lidar data at the beginning of the flight taken over a flat, dry lake. The discrepancy in altitude measurements is very small and within the scale of the ground surface roughness. A more detailed description of the Doppler Lidar and the results of the latest helicopter test flights are provided in a recent publication[4]. The analysis of the data collected from this latter helicopter flight test campaign reveals performance improvements in several aspects such as higher signal detection efficiency and lower false alarm rate.

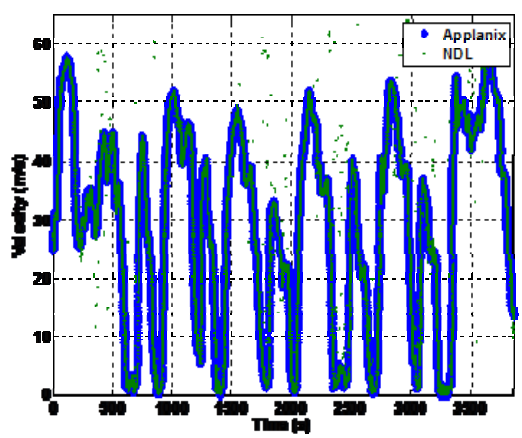

Fig. 6. Example of helicopter flight test data, comparing the magnitude of platform velocity provided by the Doppler Lidar and a high grade IMU/GPS unit (Applanix).

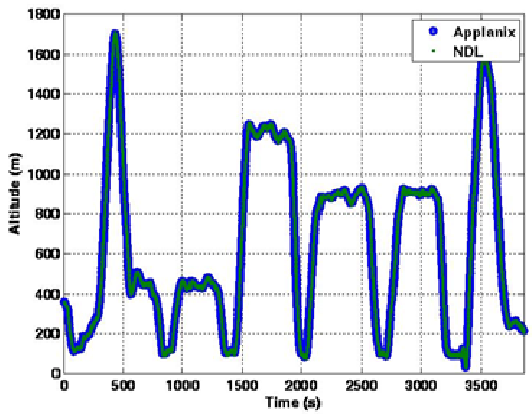

Fig. 7. AGL altitude provided by the Doppler Lidar compared with Applanix IMU/GPS data corrected for ground elevation.

4. Conclusion

A fiber-based coherent Doppler lidar, utilizing an FMCW technique, has been developed and its capabilities demonstrated through two successful helicopter flight test campaigns. This Doppler lidar is expected to play a critical role in future planetary exploration missions because of its ability in providing the necessary data for soft landing on the planetary bodies and for landing missions requiring precision navigation to the designated location on the ground. Compared with radars, the Doppler lidar can provide significantly higher precision velocity and altitude data at a much higher rate without concerns for measurement ambiguity or target clutter. Future work calls for testing the Doppler lidar onboard a rocket-powered free-flyer platform operating in a closed-loop with the vehicle's guidance, navigation, and control (GN&C) unit.

5. Acknowledgments

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6. References

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