Lidar systems for precision navigation and safe landing on planetary bodies

Farzin Amzajerdian[1], Diego Pierrottet[2], Larry Petway[1], Glenn Hines[1], and Vincent Roback[1]

[1] NASA Langley Research Center, Hampton, Virginia, 23681, United States of America
[2] Coherent Applications, Inc., Hampton, Virginia, 23666, United States of America

ABSTRACT

The ability of lidar technology to provide three-dimensional elevation maps of the terrain, high precision distance to the ground, and approach velocity can enable safe landing of robotic and manned vehicles with a high degree of precision. Currently, NASA is developing novel lidar sensors aimed at needs of future planetary landing missions. These lidar sensors are a 3-Dimensional Imaging Flash Lidar, a Doppler Lidar, and a Laser Altimeter. The Flash Lidar is capable of generating elevation maps of the terrain that indicate hazardous features such as rocks, craters, and steep slopes. The elevation maps collected during the approach phase of a landing vehicle, at about 1 km above the ground, can be used to determine the most suitable safe landing site. The Doppler Lidar provides highly accurate ground relative velocity and distance data allowing for precision navigation to the landing site. Our Doppler lidar utilizes three laser beams pointed to different directions to measure line of sight velocities and ranges to the ground from altitudes of over 2 km. Throughout the landing trajectory starting at altitudes of about 20 km, the Laser Altimeter can provide very accurate ground relative altitude measurements that are used to improve the vehicle position knowledge obtained from the vehicle navigation system. At altitudes from approximately 15 km to 10 km, either the Laser Altimeter or the Flash Lidar can be used to generate contour maps of the terrain, identifying known surface features such as craters, to perform Terrain relative Navigation thus further reducing the vehicle's relative position error. This paper describes the operational capabilities of each lidar sensor and provides a status of their development.

Keywords: Laser Remote Sensing, Laser Radar, Doppler Lidar, Flash Lidar, 3-D Imaging, Laser Altimeter, Precession Landing, Hazard Detection

1. INRODUCTION

Landing mission concepts being developed for exploration of planetary bodies are increasingly ambitious in their implementations and objectives. Most of the missions under consideration by NASA will require precision landing at the pre-designated sites of high scientific values and on-board terrain hazard detection and avoidance capability. Laser remote sensing technologies can play a major rule in enabling these missions. Currently, NASA-LaRC is developing novel lidar landing sensors under the Autonomous Landing and Hazard Avoidance (ALHAT) project[1]. These lidar sensors are 3-Dimensional Imaging Flash Lidar, Doppler Lidar, and Laser Altimeter.

To fulfill the requirements of landing at any pre-designated site under any lighting conditions, ALHAT is pursuing active sensor technology development and maturation to implement five sensor functions: Altimetry, Velocimetry, Terrain Relative Navigation (TRN), Hazard Detection and Avoidance (HDA) and Hazard Relative Navigation (HRN). The three lidar sensor systems noted above can perform these functions with some degree of redundancy. The operation of these advanced lidar sensors may be best described in the context of a lunar landing scenario as shown in Figure 1. As the landing vehicles initiates its powered descent toward the landing site at about 20 km above the surface, the Laser Altimeter begins its operation providing altitude data with sub-meter precision. This measurement will reduce the vehicle position error significantly since the Inertial Measurement Unit (IMU) suffers from drastic drift over the travel time from the Earth. The IMU drift error can be over 1 km for a Moon-bound vehicle and over 10 km for Mars. The accurate altitude data can reduce the position error to a few hundred meters in

the case of Moon. Shortly after, the Flash Lidar starts its operation by having its laser beam focused to illuminate a subset of its pixels generating a relatively low-resolution elevation data of the terrain below. The reason for reducing the divergence of the lidar transmitter beam to a fraction of its receiver field of view is to increase its operational range to about 15 km from a nominal 1 km. At this altitude, the Flash Lidar can generate a contour map of the terrain for matching them with on-board maps of known surface features such as craters. This process, referred to as Terrain Relative Navigation, will further reduce the vehicle relative position error from hundreds of meters to tens of meters. When the landing vehicle descends to about 2.5 km, the Doppler lidar initiates its operation by providing ground-relative vector velocity and altitude data with high precision of the order of 1 cm/sec and 10 cm, respectively. The Doppler lidar data will allow for precision navigation to the selected landing site to better than a meter precision. From about 1 km to 0.5 km from the ground, the Flash Lidar will operate with its full field of view generating a high resolution elevation map of the landing area identifying hazardous features such as rocks, craters, and steep slopes. This elevation map is then processed to determine the most suitable safe landing location (HDA function). Flash lidar continues to generate updated maps of the landing area. The updated maps allows for using the terrain features, such as rocks, as marker for establishing a trajectory toward the selected landing location. This phase of Flash Lidar operation is referred to as Hazard Relative Navigation. The Flash Lidar operation is ceased at about 100 m above the ground before the vehicle thrusters create a dust plume. The high precision velocity and altitude data provided by the Doppler Lidar allows the Guidance, Navigation, and Control system to direct the vehicle to the identified landing site and ensure a safe and smooth landing.
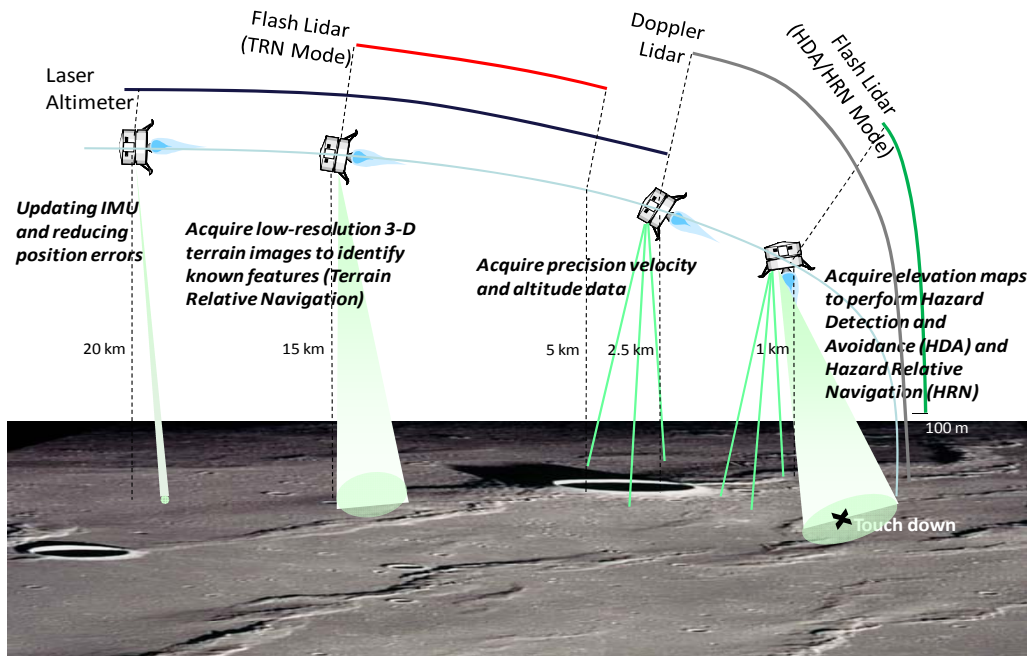

Fig. 1. Operational Scenario of Landing Sensors.

2. LIDAR SENSORS OPERATIONAL DESCRIPTION

The performance and operational requirements of the lidar sensors are driven by the ALHAT project goals summarized per following:

- Autonomous operation under any lighting conditions and any landing location
- Global Landing Precision: Landing to within 30 meters of predetermined location in the case of lunar landing
- Hazard Detection: Terrain features greater than 30 cm in height and slopes greater than 5 degrees over the vehicle footprint (~ 10 m)

− Local Landing Precision: Landing to within 1 m error at the safe location selected by the onboard Hazard Detection and Avoidance algorithm

Table 1 below lists the ALHAT sensor suite and their top level performance specifications for performing each of the five required functions with some degree of redundancy. Flash Lidar is capable of performing all the functions with exception of velocimetry for which a Doppler Lidar is being developed. The ability of the Doppler Lidar to provide velocity data with approximately 1 cm/sec is highly attractive for precision landing. Additionally, the Doppler Lidar provides high resolution altitude and ground-relative attitude data that may further improve precision navigation to the identified landing site. The Laser Altimeter provides independent altitude data over a large operational altitude range of 20 km to 100 m. All three laser sensors have a nominal update rate of 30 Hz. Although the Flash lidar is fully capable of providing the necessary altitude data, the Laser Altimeter is used in the operational scenario of Figure 1 in order to lessen spacecraft accommodation issues. Since the orientation of the spacecraft will be different during different phases of descent and landing, it may be difficult to accommodate the Flash Lidar such that it will have a clear view of the ground during the approach phase (< 2km altitude), when it needs to perform HAD and HRN functions, as well as powered descent phase (20 km – 10 km altitude), when Altimetry and TRN functions need to be performed. Therefore, the Laser Altimeter can reduce the complexity of spacecraft accommodation design and ease the spacecraft attitude control requirements. Even if the Flash lidar can operate over the entire powered descent phase, the Laser Altimeter may serve as a redundant sensor for either or both Altimetry and TRN functions.

Table 1. ALHAT Sensors Performance Requirements.

Sensor	Function	Operational Altitude Range	Precision/Resolution
Flash Lidar	HDA/HRN	1000 m – 100 m	5 cm/40 cm
	TRN	15 km – 5 km	20 cm/6 m
	Altimetry[1]	20 km – 100 m	20 cm
Doppler Lidar	Velocimetry	2500 m – 10 m	1 cm/sec
	Altimetry	2500 m – 10 m	10 cm
Laser Altimeter	Altimetry	20 km – 100 m	20 cm
	TRN[1]	15 km – 5 km	20 cm

[1] Secondary function, maybe considered as redundancy option.

3. 3-DIMENSIONAL IMAGING FLASH LIDAR

The capabilities of the Flash Lidar technology for autonomous safe landing application have been investigated through a series of static and dynamic experiments at the NASA-LaRC sensor test range, and from helicopter and fixed-wing aircraft platforms[2-4]. All the Flash Lidar experiments to date have been based on the 3-D Imaging camera technology developed by Advanced Scientific Concepts (ASC)[5]. This 3-D Imaging camera has a 128x128 pixel array capable of generating real-time image frames at up to 30 Hz rate. In addition to demonstration of Flash Lidar capabilities, these tests served several other important objectives. One of these objectives was to define areas of technology improvement required to meet NASA's autonomous safe and precision landing needs. Another objective was to support the development of algorithms for the HDA, HRN, and TRN functions and analyze their respective performance towards achieving the specified goals. The analyses of data collected from these tests allowed for improving the Flash lidar computer models used in the end-to-end landing system simulations. The tests data also proved invaluable for the development of image reconstruction and enhancement algorithms that can result in generation of elevation maps of the extended landing site from about 1 km altitude.

Earlier static and airborne tests resulted in initiation of a series of Flash Lidar component technology advancement projects in 2008, conducted in collaboration with industry, aimed at the development of a Flash Lidar landing sensor system that can efficiently perform the ALHAT functions described above. The Flash Lidar component technology projects and their status are summarized in Table 2. These activities include the development of low noise 256x256 pixel Avalanche Photodiode array, high sensitivity 256x256 Readout Integrated Circuit (ROIC), rugged and compact transmitter laser with optimum pulse temporal and spatial profiles, programmable field-of-view receiver optics, and novel signal processing techniques. These technology advancements have resulted in significant increase

in operational range by more than a factor 3, higher frame rate, and a much more robust system. Table 3 summarizes the current state of the Flash Lidar technology and the performance goal of ongoing technology advancement activities.

The primary performance requirement of the Flash Lidar is to generate a Digital Elevation Map (DEM) of an area at least 100 m X 100 m in dimensions from 1000 m slant range with a Ground Spot Distance (GSD) of 10 cm and elevation precision of 5 cm. The development of larger format detector and ROIC of 256x256 pixels will help achieving the specified Flash Lidar performance requirements. Current 128X128 pixels camera will require a mosaic of over 100 image frames in order to create the required DEM. With 10 cm GSD, each frame will cover only 12.8 m X 12.8 m area and accurate registration of each image frame will require significant overlapping of the image frames. Therefore, the total number of image frames will be larger than $(100m/12.8m)^2 = 61$. The larger format detector and ROIC of 256x256 pixels will reduce the number of frames by a factor 4 thus making the generation of 100 m^2 DEM considerably easier and faster. The ongoing development of ROIC will also improve the range measurement precision from current 8 cm to 5 cm required for detecting 30 cm hazards with high reliablity[6]. The 256X256 focal plane array (detector + ROIC) is expected to have higher sensitivity by at least a factor of 4 and half the pitch size compared with current focal plane, thus allowing the use of the same laser and receiver optics.

Table 2. Flash Lidar Component Technologies Advancement.

Component Technology	Description	Lead Organization	Status
Transmitter laser	High pulse energy optimized for Flash Lidar, compact and rugged design suitable for space	Fibertek	Complete
Detector Array	Low noise InGaAs Avalanche Photodiode Detector array	Optogration	Complete
Image reconstruction and enhancement processor	3-D Super-resolution algorithm, real-time implementation in high-speed HDW	NASA LaRC	2012
Fiber optic delivery unit	High pulse energy fiber cable for transmitter beam, rugged designed for space	NASA GSFC	2012
256X256 Sensor Engine	Low noise HgCdTe APD detector with advanced ROIC including control/interface electronics	Raytheon	2012
256X256 Sensor Engine	Advanced high sensitivity ROIC hybridized with Optogration APD array including control/interface electronics	ASC	2013
Receive/Transmit Optics	Variable Field of View	NASA LaRC	2013

As an alternative to building a mosaic of large number of image frames for creating a DEM with sufficient dimensions, a novel image resolution enhancement technique is being pursued that can eliminate the need for precision scanning of the lidar and significantly reduce the DEM construction time. The image resolution enhancement can be achieved by means of a super-resolution algorithm in real-time. The super-resolution algorithm is based on the back projection method that has recently been applied to solve the super resolution problem in the 2-D environment[7]. Analysis of processed Flash Lidar data indicates that 8 times resolution enhancement is feasible. Study of the processed data also shows reduction in random noise as multiple image frames are blended to create a single high resolution DEM. A real-time super-resolution processor is currently being developed to demonstrate its potentials for landing application.

Table 3. Flash Lidar Current State and Performance Goals.

Parameter	Current	Goal
Max operational range	1400 m	1400 m
Number of pixels	128X128	256X256
Field of view	Fixed 1, 3, 5 deg	Variable 6 – 24 deg
Elevation precision	8 cm	5 cm
Frame update rate	20 Hz	30 Hz

4. DOPPLER LIDAR

The Doppler Lidar is a versatile instrument capable of providing precision velocity vectors relative to the sensor reference frame, vehicle platform altitude, and ground relative attitude. With this sensor the landing vehicle can acquire a surface inertial navigation fix during the approach phase, accurate to a few centimeters in position and about one centimeter per second in velocity. This allows the vehicle to accurately navigate from a few kilometers altitude to the previously defined surface location very accurately.

The Doppler Lidar obtains high-resolution range and velocity information from a frequency modulated continuous wave (FMCW) laser waveform whose instantaneous frequency is modulated linearly with time. Figure 2 shows the waveform's frequency content versus time, and the resulting intermediate frequency (IF) that holds the desired range and velocity information. The green triangular waveform represents the frequency content of the transmitted waveform, and the blue trace simulates a received waveform. The horizontal shift to the right of the received waveform is due to the time delay caused by the round trip time of flight of the laser beam to the target. The vertical shift of the received waveform represents the Doppler frequency change that arises from the motion of the vehicle relative to the ground.

The lidar design uses an optical homodyne receiver configuration, in which a portion of the transmitted beam serves as the reference local oscillator (LO) for the optical 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 (red) trace in Figure 2. The IF trace shows two distinct frequencies, one caused by the up-ramp, and one caused by the down-ramp of the waveform. The difference in up-ramp and down-ramp frequency provides the vehicle velocity and their mean value provides the range to the ground.   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.

A breadboard Doppler Lidar was assembled and tested onboard a helicopter in 2008 to evaluate its capabilities for the landing application. The results of helicopter test showed excellent agreement with the high accuracy GPS derived velocities. The data collected during the flight tests also proved to be very valuable for the development of a compact and efficient system, shown in Figure 3, which was demonstrated in a helicopter flight test campaign in 2010. Examples of this flight test data are provided in Figure 4 where the Doplpler 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 showed excellent

Fig. 2. The laser frequency modulation has a linear chirp waveform. Received waveform is delayed in time. Lower trace is the difference between transmit and receive waveforms.

agreement with the IMU/GPS data. With the scale of these plots, the Doppler Lidar and IMU/GPS data essentially overlap and not distinguishable. The mean value of discrepancy in magnitude of the vector velocity measurements was about 3.5 cm/sec. Quantifying the discrepancies between the Doppler Lidar and IMU/GPS measurements of altitude is not as straight forward since the GPS measures altitude relative to sea level while the Doppler Lidar provides altitude relative to the local ground. For the altitude plot of Figure 4, a fixed bias was subtracted from the GPS data so it can 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
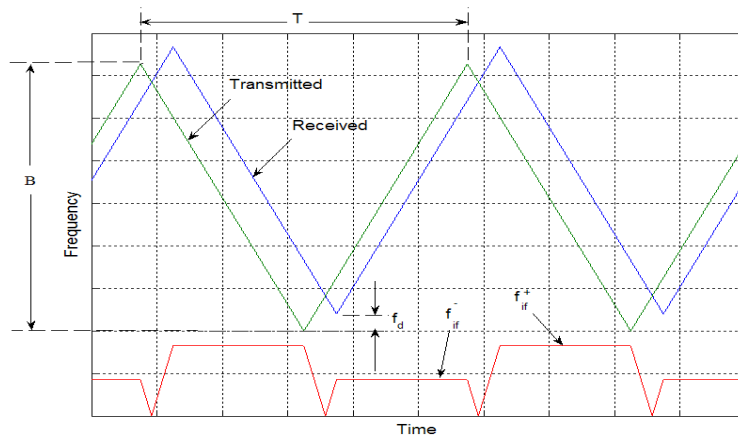
discrepancy in altitude measurements is very small and within the scale of the ground surface roughness. A more detailed description of the Doppler Lidar and the results of the latest helicopter test flight are provided in a recent publication[8].

Fig. 3. Doppler Lidar prototype system with a fiber-coupled optical head having 3 lenses pointing to different directions. The Doppler Lidar provides vehicle vector velocity and altitude.
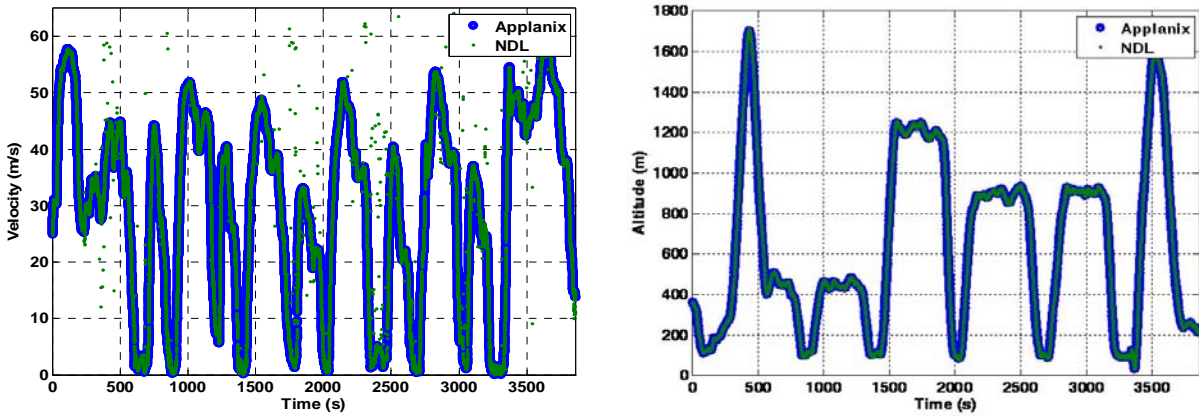

Fig. 4. Example of helicopter flight test data, comparing the magnitude of platform velocity and AGL altitude provided by the Doppler Lidar and a high grade IMU/GPS unit (Applanix).

5. LASER ALTIMETER

The vehicle altitude can be measured by the Flash Lidar at high altitudes approaching 20 km and the Doppler Lidar from altitudes of a few km's above the ground. However, a separate Laser Altimeter sensor can ease the spacecraft accommodation design and provide a redundancy to this critical data. A Laser Altimeter has been designed and built specifically for ALHAT. The breadboard version of this sensor was first tested in the fixed-wing aircraft test from altitudes over 8 km in 2008. A compact and low-power prototype system, as shown in Figure 5, was recently completed and tested at the NASA-LaRC lidar test range facility. The results of measurements indicated that the Altimeter sensor exceeds the requirements of Table 1. The measured performance parameters were 30 km maximum operational range, 8 cm range precision, and an accuracy of 0.0034% of range. This system operates at an eye safe energy level at 1.5 micron wavelength for easier terrestrial operation and testing.
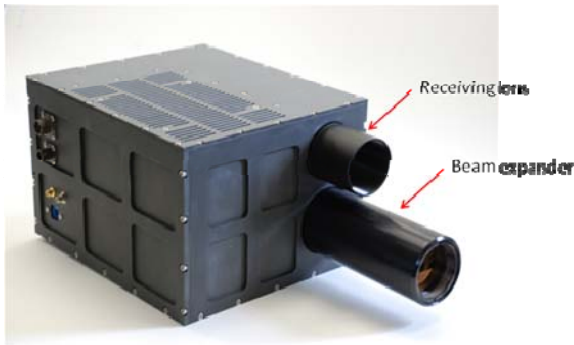
Fig. 5 Laser Altimeter Sensor.

6. CONCLUSION

Lidar has been identified by NASA as a key technology for enabling autonomous precision safe landing of future robotic and crewed lunar landing vehicles. NASA-LaRC has been developing three laser/lidar sensor systems under the ALHAT project. The capabilities of these Lidar sensor systems were evaluated through a series of static tests using a calibrated target and through dynamic tests aboard helicopters and a fixed wing aircraft. The airbone tests were perfomed over Moon-like terrain in the California and Nevada deserts. These tests provided the necessary data for the development of signal processing software, and algorithms for hazard detection and navigation. The tests helped identify technology areas needing improvement and guiding ongoing technology advancement activities.

ACKOWLEDGMENTS

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