A HAZARD DETECTION SENSOR FOR LANDING ON EUROPA

A. Miguel San Martin*, E. David Skulsky, Nikolas Trawny, and Anup Katake

Jet Propulsion Laboratory, California Institute of Technology, USA
Alejandro.M.Sanmartin@jpl.nasa.gov

ABSTRACT

Based on the limited imagery available, the surface topography of Jupiter's icy moon Europa is expected to be hazardous for robotic landers. The Europa Lander Concept Pre-Project Team has therefore concluded that onboard hazard detection (and avoidance) using an imaging light detection and ranging (lidar) system is an enabling technology. In this paper we describe the challenges, requirements, technical solution space, and our maturation strategy to advance lidar technology for a Europa Lander mission concept to TRL 6 by 2021. JPL is confident that the resulting technology will be of value to a wide range of lunar and planetary landing missions.

1 INTRODUCTION

The Jet Propulsion Laboratory is currently investigating a Europa Lander mission concept that would search for evidence of life, assess its habitability via in situ techniques, and characterize the surface and subsurface to enable future robotic exploration [1]. However, autonomous safe and precise landing on Europa poses unique challenges.

The currently available surface imagery from the Voyager and Galileo spacecraft is limited in resolution. Roughly 10% of Europa's surface is imaged at scales of ≤ 250 m/pixel, while the rest is imaged at scales upwards of 1 km/pixel [2]. The highest resolution images (6-12 m/pixel) cover only 0.0001% of the surface. From the available data, it is theorized that meter-scale landing hazards, such as such as blocks, pits, domes, cracks, ridges, penitentes, icebergs or rafts are plausible [1]. The Europa Clipper mission is planning to image at least forty sites, ≥ 2 km × 4 km in area, at ≤ 1 m/pixel spatial resolution, thus vastly improving the ability to pre-select a safe landing site [1]. However, even this scale is insufficient to reliably detect all terrain features hazardous to a small robotic lander, motivating the need for an onboard active hazard detection sensor [5].

High-energy electrons and protons trapped by Jupiter's magnetic field result in an extremely intense ionizing radiation environment, which substantially affects sensor performance, possible modes of operation, sensor component selection, and flight qualification. Based on the current mission design trajectories and the GIRE-2p Jovian radiation model, the Lander is expected to experience a total ionizing dose (TID) of ~1.7 Mrad, primarily from electrons, behind 100 mil of aluminum (Si equivalent). Most Lander electronics will likely be housed in a radiation vault similar to that used on Juno, which would decrease the expected TID to 150 krad (Si) or less. All electronics within the vault would need to be rated to 300 krad to maintain a radiation design factor of two (RDF = 2) [4].

Europa Lander would have to comply with NASA planetary protection procedural requirements [3] and, as an anticipated Category IV mission, the probability of contamination (defined as the introduction of a single viable terrestrial microorganism) must be less than 10^{-4}. The implication of these requirements on Lander hardware, including the hazard detection sensor, is that it must be sterile before it reaches the surface. The planetary protection strategy would likely consist of several sterilization techniques including cleaning and dry-heat microbial reduction (DHMR). For components which can be neither cleaned nor heated, the project would consider incineration devices onboard the vehicle to destroy any residual biological material.

Finally, the launch mass to landed mass ratio for a Europa lander is approximately 50-to-1 (i.e., for every kilogram delivered to the surface of Europa, approximately 50 kg of launch mass is required). This results in the need to minimize size, weight, and power (SWaP) through optimized sensor design, packaging, and shielding.

2 METHODOLOGY

The Europa Lander Deorbit, Descent, and Landing Concept of Operations is illustrated in Figure 1. The sequence starts with a Deorbit Burn that uses a solid rocket motor (SRM) to reduce the velocity from ~1900 m/sec to ~70 m/sec. At burnout, the vehicle is at an altitude of 5 km. After jettisoning the SRM, the spacecraft turns to nadir to perform Terrain Relative Navigation (TRN). The TRN function uses a passive imager, a laser altimeter, a dedicated vision compute element, and an on-board map to compute the absolute location of the vehicle in a Europa fixed frame and its 3-axis velocity relative to the ground. This information is then used to clean the trajectory delivery errors by performing a precision landing maneuver that delivers the vehicle to a 100 m radius ellipse centered around the targeted landing site and at 1 km altitude. The vehicle then starts a vertical descent trajectory until it reaches 500 m altitude where the Hazard Detection and Avoidance phase begins.

During the Hazard Detection and Avoidance phase the 3D lidar first scans an area of 100 m × 100 m, and creates a digital elevation map (DEM) with a 5 cm (3σ) voxel resolution in one second. The following second is then used to compute hazards over the 1.5 m radius lander footprint and select a landing site that avoids them. The third second is margin. The landing sequence continues by performing a trajectory maneuver that brings the lander over the safe landing zone, followed by precision velocimetry and altimetry starting at 100 m, and finally, by landing using the same SkyCrane technique employed in the Mars Science Laboratory.

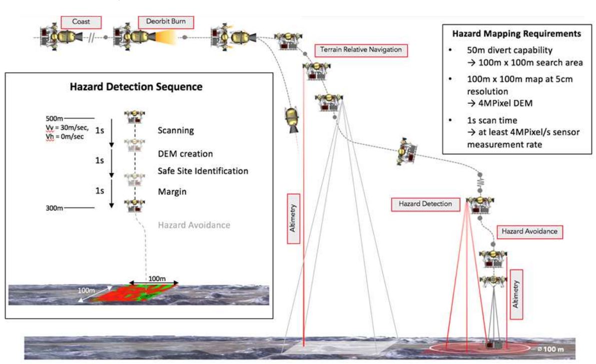

Figure 1 Deorbit, Descent, and Landing ConOps

During the 3D lidar image acquisition period the vehicle is descending at a nominal 30 m/sec vertical velocity and zero horizontal velocity with variations of up to 0.7 m/sec. The nominal attitude is with the sensor boresight pointing along the vertical with variations of up to 0.1 deg. The attitude knowledge can be assumed to be perfect but the 3-axis velocity knowledge can have an error of up to 0.6 m/sec that remains constant during the entire frame acquisition.

The SWaP requirements are: mass including radiation shielding < 7 kg, power < 50 W, volume < 25 cm x 25 cm x 25 cm (optical head and lidar signal processor, each).

The purpose of the Europa Lander lidar development is to field a sensor that fulfills the combined altimetry and hazard detection functions described above.

2.1 State of the Art

The driving requirement for the sensor is the measurement rate of 4 million range measurements per second from an altitude of 500 m (Figure 2). The state-of-the-art in planetary missions is represented by the OSIRIS-Rex Laser Altimeter (OLA) [6], with a measurement rate of 10,000 range measurements per second from up to 1 km altitude. While there are terrestrial sensors that can achieve higher range measurement rates from higher altitudes, none meets the Europa Lander SWaP, DEM generation time, and radiation requirements.

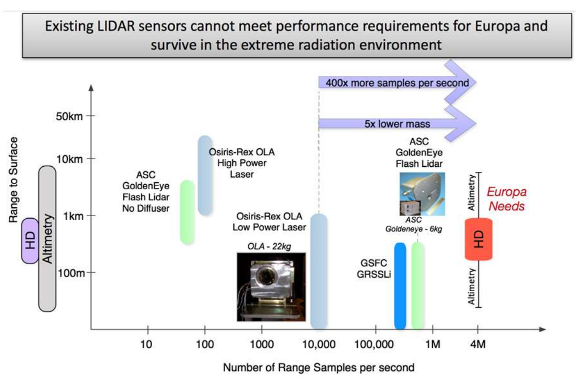

Figure 2 3D-Lidar State of the Art

2.2 New Approach

In order to meet these sensor development challenges, the Europa Lander team performed several technology surveys, including an RFI and an RFP, of the technology and industry capability around the world. The following is a brief summary of the technologies we surveyed.

<u>Detection:</u>

The detection technique drives the number of photons required to achieve a certain probability of detection and meet the range accuracy requirements, which have a large impact on sensor SWaP. It also drives the amount of processing required to produce a valid measurement as well as robustness to background noise. The different detection techniques can also present different degrees of challenges when it comes to constructing large sensor arrays. Finally, the intense radiation environment imposes strong requirements on the detector materials which can impact the detection technique.

The choices of detection techniques include Coherent vs. Incoherent Detection, and Continuous Wave (CW) vs. Pulsed Time-of-Flight (TOF). The Pulsed TOF detection options are Geiger Mode, Single Photon, and Linear Detection. The result of the technology survey narrowed the options to these three Pulsed TOF techniques.

<u>Frame Acquisition:</u>

Frame acquisition refers to how the range measurements are collected over the map area. There are three approaches: 1) scanning a single range detector in two axes over the area to be mapped, 2) flashing a detector array over the entire mapping area (i.e., no scanning is required), and 3) a hybrid approach in which an array of detectors is scanned in one or two axes. The first approach places challenging requirements on the scanning mechanism while the second approach is a challenge for the detector array and required laser power. The hybrid approach is a compromise which was embraced by most of the proposers and is the only one being pursued by Europa Lander at this time.

It is important to note that in any sensor concept which requires scanning—including the hybrid approach—the motion of the vehicle and the velocity and attitude knowledge errors during frame acquisition can result in map artifacts which are indistinguishable from real hazards (e.g., holes and seams). This is a critical consideration when selecting the size and shape of the detector array and the scan pattern and speed.

The FOV size ($18° \times 18°$) of the sensor for this application opens up a large option space for scanning mechanisms: fine steering mirrors (FSM), rotating polygonal mirrors, galvo mirrors, and Risley prisms. Solid state scanning and MEMS mechanisms are not currently under consideration because of TRL, development risk, concerns about radiation, and/or incompatibility with the application.

<u>Overall Architecture:</u>

The other architectural choices that are being explored and that are unique to the Europa Lander application are: separate altimeter vs. common laser/detector for both functions, single box vs. separate optics and electronic boxes. We are also exploring several sensor output options like a single fully-registered DEM at the end of the scan vs. continuous registered maplets during the scan.

2.3 Describe the Future State

This development effort is already bearing fruit by defining a clear use case for hazard detection for planetary landings, including requirements and constraints, which is relevant to many missions, pushes the state-of-the-art in a realistic way, and provides focus to industry and government R&D efforts (e.g. SBIR's, internal R&D, etc.).

2.4 Risks and Rewards

Radiation is the dominant risk followed by development risks (cost and schedule). As described in the following sections, these risks are mitigated by following a gradual and disciplined development strategy that retires risks through early testing and by avoiding premature selection of technologies and teams.

If successful, the 3D lidar sensor developed through this effort not only will enable the Europa Lander mission but will also have major uses in other lander applications: Mars, Moon, Comets, or Asteroids.

3 PROGRAMMATICS

The Europa Lander study team, including upper management, decided early that hazard detection and avoidance was an enabling capability for that mission and, as a result, started generating a plan to develop a hazard detection sensor. This decision was informed by prior hazard detection work conducted by JPL as part of the Autonomous Landing and Hazard Avoidance Technology (ALHAT) program [7], ongoing SBIR work on lidar for hazard detection, and a general survey of the commercial technology that indicated that hazard detection sensing technology was at the right development level to be infused into Europa Lander.

3.1 Strategic Approach

The Europa Lander 3D lidar requirements were derived by adapting the ALHAT concept of operations to the Europa Lander concept of operations and adjusting the DEM accuracy requirements to the physical characteristics of the lander.

It was recognized early on that to achieve the required high measurement rate the sensor architecture would have to employ an array of multiple detectors and an effort was started to study the maturity and radiation susceptibility of such detector arrays. For this purpose, funding from STMD Ocean Worlds was used to issue several study contracts to companies and academia with expertise in the field; these were small studies with a duration of three months. The conclusion from these studies was that there were multiple detector array approaches which could support the required measurement rates and survive/perform in the harsh radiation environment.

The next step was to issue an RFI for a full sensor concept. The responses to the RFI allowed us to gauge the interest in the private sector for participating in the sensor development and to survey once again the technologies that could be employed in such a sensor.

At this point a sensor development strategy was formulated to try to avoid the shortcomings in previous efforts where the technology and the developing organization were down-selected too early in the process. The resulting strategy is centered on bringing two sensor concepts to TRL-6 by Europa Lander PDR in 2021, each concept developed by independent teams and, desirably, using competing technologies. The plan is also for both efforts to produce a fieldable sensor breadboard for performance testing in a relevant flight envelope by JPL. In addition, the two teams must show that the sensor concept can be built into flight units that meet SWaP requirements and that it can be flight qualified to survive and perform in the expected space environment (vibration, shock, thermal, radiation). Radiation is of particular concern and each team is expected to provide and execute a plan that includes the proper combination of parts analysis and, for key components in the sensor architecture, radiation tests.

The development effort is divided into three phases with two gates between them for down-selection or termination. During the first phase the requirements are finalized, the concept and technology refined, and the plan for dealing with radiation developed. The second phase is a detailed design phase, continuation of component radiation testing and other risk mitigation efforts. During the third phase, the component radiation testing is finalized and the fabrication and assembly of the breadboard is completed. It is also expected that during the third phase a proposal to develop the flight instrument will be generated by each team.

We have selected three teams for the first phase of the effort to be selected down to two at the end of the phase.

One of these three teams is a commercial company, Sigma Space LLC., which was selected through a rigorous competitive process by issuing an RFP and selecting a winner. The second team is MIT/Lincoln Laboratory (MIT-LL), a federally funded research and development center (FFRDC) with expertise in Geiger Mode lidar. The third team is NASA Goddard Space Flight Center (GSFC) with expertise in lidar for space applications.

After all contracts are completed and after the tests of the breadboards and evaluation of the proposals are finished, the Europa Lander team will decide on the strategy for the development of the flight units. Among the possible strategies, and depending on the results of the ongoing effort, the project may elect to pursue a single source award to implement one of the concepts developed by the current effort or to open the competition to other teams and technologies by issuing an RFP. The second scenario might include an important relaxation of requirements based on what we would have learned so far.

3.2 Development Plans and Milestones

The current effort must achieve TRL-6 by Europa Lander PDR in 2021. The six-month long Phase 1 development is currently near completion. Phase 2 is also planned for a six-month duration and Phase 3 for 18 months.

3.3 Partnering

Building on more than 10 years of partnering with NASA Johnson Spaceflight Center (JSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC) in ALHAT and SPLICE in hazard detection, JPL has engaged ALHAT leadership to support the Source Evaluation Team for the Europa Lander Hazard Detection lidar.

The teams that have been selected for Phase 1 include a NASA center, GSFC, an FFRDC, MIT-LL, and a commercial company, Sigma Space LLC.

JPL continues to engage the commercial sector and academia through SBIRs and other study contracts.

3.4 Overcoming the Valley of Death

The Europa Lander mission concept study has determined that hazard detection and avoidance is a mission enabling technology and has recommended that the project funds the development of the sensor.

4 WIDER VISION

The Europa Lander mission concept study had to consider technologies that could achieve TRL-6 by 2021. Among the technologies that were left out and that should be pursued by NASA with separate funding are: Coherent detection for combined Doppler velocimetry including optical microchips, different detector materials for lower noise (e.g. MerCadTel), continuous wave (CW) concepts that leverage image sensors, solid state beam steering approaches, and improved linear mode detector arrays.

In addition, NASA should consider leveraging the large developments and advances being pursued by the auto industry.

5 CONCLUSIONS

The Europa Lander mission concept study is currently engaged in the development of a high-performance 3D-lidar for hazard detection that must survive and perform in the harsh radiation environment of Europa.

The sensor development approach leverages the best technology and expertise provided by government agencies and the private sector.

If successful, the 3D-lidar sensor developed by this effort not only will enable the Europa Lander mission but it will also have major utility for other lander applications: Mars, Moon, Comets, Asteroids.

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