Medium Altitude Airborne Geiger-mode Mapping Lidar System

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ABSTRACT

Over the past 15 years the Massachusetts Institute of Technology, Lincoln Laboratory (MIT/LL), Defense Advanced Research Projects Agency (DARPA) and private industry have been developing airborne LiDAR systems based on arrays of Geiger-mode Avalanche Photodiode (GmAPD) detectors capable of detecting a single photon. The extreme sensitivity of GmAPD detectors allows operation of LiDAR sensors at unprecedented altitudes and area collection rates in excess of 1,000 km²/hr. Up until now the primary emphasis of this technology has been limited to defense applications despite the significant benefits of applying this technology to non-military uses such as mapping, monitoring critical infrastructure and disaster relief. This paper briefly describes the operation of GmAPDs, design and operation of a Geiger-mode LiDAR, a comparison of Geiger-mode and traditional linear mode LiDARS, and a description of the first commercial Geiger-mode LiDAR system, the IntelliEarth™ Geospatial Solutions Geiger-mode LiDAR sensor.

Keywords: LiDAR, LADAR, Geiger-mode, avalanche photodiode, single photon, mapping, FOPEN

1. INTRODUCTION

LiDAR systems based on avalanche photodiodes operating in Geiger-mode have been under continuous development since the late 1990’s at the Massachusetts Institute of Technology, Lincoln Laboratory (MIT/LL) [1,2,3,4,5]. Since then, several airborne Geiger-mode LiDAR systems have been developed: JIGSAW, a low altitude foliage penetration (FOPEN) LiDAR shown in Figure 1 [6,7], the Airborne Lidar Research Testbed (ALIRT) a medium altitude mapping LiDAR [8], the High Altitude Lidar Operations Experiment (HALOE) a high altitude imaging LiDAR [9] and the MIT/LL MACHETE a medium altitude FOPEN LiDAR system. DARPA facilitated the transfer of GmAPD technology from MIT/LL to Princeton Lightwave Inc. [10, 11], and Boeing Spectrolab [12], in order to establish commercial sources of GmAPD based LiDAR cameras.

During the same period, compact, neodymium-doped yttrium aluminum garnet (Nd:YAG) Diode Pumped Solid State Lasers (DPSSLs) with high pulse energies, high pulse repetition rates (PRFs) and subnanosecond pulse widths were also under development. The maturation of these two complementary subsystems has made a commercial GmAPD LiDAR capable of collecting high resolution LiDAR data at area coverage rates (ACRs) exceeding 1,000 square kilometers per hour technically and economically feasible.

This paper briefly describes the operation of GmAPDs, the basic design and operation of a Geiger-mode LiDAR, a comparison of Geiger-mode and traditional linear mode LiDARS, and a description of the first commercial Geiger-mode LiDAR system, the IntelliEarth™ Geospatial Solutions Geiger-mode LiDAR sensor (Harris Geiger-mode LiDAR).

Figure 1. Jigsaw FOPEN Geiger mode LiDAR System (2005)
2. GEIGER-MODE AVALANCHE PHOTODIODE LIDAR

Geiger-mode Avalanche Photodiode Detector Operation

In linear mode, when the reverse-bias voltage across an avalanche photodiode is maintained below a critical level the output current is linearly proportional to the incident photon flux. Above this critical level, or avalanche breakdown voltage, the absorption of a single photon can create an avalanche current pulse large enough to be detectable by digital timing circuitry. When operated with a reverse-bias voltage above the avalanche breakdown voltage, the APD is in Geiger-mode. Thousands of GmAPDs can be integrated into focal plane arrays (FPAs) with integral time-of-flight (TOF) counters and associated readout integrated circuitry (ROIC). In addition, because the active area of the detector is relatively small compared to the spacing between adjacent detectors, a microlens array with a dedicated lens for each detector is added to increase the effective fill factor to ~75%. This maximizes the probability for any photon incident on the FPA to be detected (Figure 2).

The operation of a GmAPD LiDAR is conceptually very simple. A laser pulse is used to illuminate a scene. By precisely measuring the TOF of the photons reflected off the scene the three dimensional coordinates of features within the scene can be determined.

Figure 3 shows the timing sequence of a GmAPD imaging cycle. T₀ is defined by when a transmit laser flash is detected. Increasing the bias on the array (arming) is delayed based on a priori knowledge of the approximate distance to the target. Following the arm delay, the capacitance of each GmAPD is charged up to the desired overbias voltage, determining the effective sensitivity or Photon Detection Efficiency (PDE) of the detectors in the array. Once the pixels are armed, the voltage source is disconnected, and any subsequent avalanche event simply discharges the diode capacitance, with the associated current flow limited to just the amount of charge needed to remove the overbias from the detector.

Once the array has been over-biased and operating in Geiger-mode, the range gate is opened by starting the ROIC TOF counters. The range gate duration is chosen to completely encompass the volume of interest. While the range gate is open, photons incident on a detector may be converted into a photoelectron, which in turn may cause an avalanche, latching the TOF counter of the detector. Once the gate is closed, the over bias is removed, the array TOF values are read out and the array is then ready for another cycle.
Key Characteristics of GmAPDs

- Single-photon sensitivity.
  - Reduces system size, weight and power
  - Allows operation at high altitude
- Compact detection circuitry makes fabrication of large arrays of detectors practical.
- Large avalanche current flow with sharp leading edge is detectable by simple CMOS digital timing circuitry.
- Noiseless readout using digital detection
- Low timing jitter of $< 500$ ps
- Large avalanche current flow causes “after-pulse” avalanches due to carrier trapping and de-trapping if the array is re-armed before the de-trapping process has completed which limits the detection rate of any given pixel [13].
  - Since the duration of the de-trapping process is on the order of hundreds of nanoseconds, compared to the maximum frame rate of current GmAPD cameras which is on the order of hundreds of kilohertz, after-pulsing has no impact on performance of the system.
- Hot carrier luminescence during avalanches can cause photon emission, resulting in optical crosstalk between detectors.
  - Crosstalk can be reduced by FPA designs incorporating trenches between detectors, reduced detector active area diameters, antireflective coatings, as well as reducing the sensitivity of the FPA and post collection processing.
- A GmAPD detector as currently implemented has only one measurement opportunity per imaging cycle, once the detector has avalanched it cannot detect any subsequent photons until the current imaging cycle is completed and the detector is rearmed. The time between the avalanche and when the detector can again detect an incoming photon is referred to as blanking loss.
  - Compensated for by high PRF lasers and large detector arrays, enabling sample rates in excess of 400 MS/s
  - Similar to after-pulsing, the current and projected synchronous frame rates of GmAPD FPAs and repetition rates of short pulse high energy laser transmitters, blanking loss currently has no impact on the performance of a direct detection TOF based system.
  - Blanking loss is not an inherent limitation of GmAPDs. Future asynchronous ROICs will enable multiple TOF measurements per imaging cycle.

Basic Measures of Performance of Geiger-mode Avalanche Photodiodes

Two primary measures of performance of a GmAPD detector are the Photon Detection Efficiency (PDE) and the Dark Count Rate (DCR). [14]

PDE is the probability that an incident photon causes the detector to fire and is a combination of the quantum efficiency of the detector and the probability that an avalanche occurs when a single photon reaches the detector. However, if the average number of photons per pulse is greater than one, the effective Multi-photon PDE (PuDE) increases significantly. For example, for a GmAPD FPA with a single photon PDE of 30% receives an average of ten photons per pulse the PuDE increases to 98%. [10]

DCR is the probability that a detector fires in the absence of a photon and is expressed as counts per second per detector and expressed in kHz. At a PDE of 30% a typical DCR is on the order of 20 kHz so during a 4 microsecond 600 meter range gate an average of 0.08 noise photoelectrons will be randomly distributed through the range gate for each detector. DCR has significantly less impact than solar background and can be ignored in most daytime radiometric analyses.

Geiger-mode and Linear mode LiDAR systems

Geiger-mode and linear mode LiDARs are two different methods of accomplishing the same task, which is to reconstruct the TOF waveform returned from the scene of interest. While a linear...
mode system samples the entire waveform in a single flash, a Geiger-mode system samples the waveform one flash at a time at a very high sample rate. For example, the waveform shown in Figure 4 is the number of counts per range bin collected over multiple flashes of a GmAPD LiDAR. The GmAPD LiDAR samples the waveform one point at a time, so unlike a linear mode LiDAR, does not require a high speed digitizer which results in a simpler, highly scalable and more cost effective implementation.

In medium and high altitude applications a GmAPD LiDAR has a significant advantage over traditional linear mode linear mode systems due to the single photon sensitivity of the detectors. Compared to a GmAPD LiDAR, a traditional linear mode system requires at least an order of magnitude more photons for a detection which in turn drives up the average power requirements and overall size, weight and power (SWaP) of the system making a medium or high altitude linear mode LiDAR impractical.

Another difference between a GmAPD LiDAR and linear mode LiDAR is the method of building an intensity image. The linear mode LiDAR is capable of creating an intensity image in a single flash, while a GmAPD requires multiple flashes to build up an intensity image of the scene which may be illuminated by the transmit laser or solar background as shown in Figure 5.

3. INTELLIEARTH™ GMAPD LIDAR SENSOR

Sensor Hardware

![Image of a sensor](image-url)

**Figure 5.** Geiger mode APD 2D relative intensity image

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**Figure 6.** Harris IntelliEarth™ Geospatial Solutions Geiger-mode LiDAR sensor on alignment stand in the optical laboratory
The Harris IntelliEarth™ Geospatial Solutions Geiger-mode LiDAR sensor is the first commercial airborne LiDAR system that takes advantage of the single photon capabilities of the Geiger-mode avalanche photodiode (Figure 6).

The primary components of the system (Figure 7):

- 128x32 InP/InGaAsP Geiger-mode camera capable of readout rates in excess of 100 kHz (1)
- Compact Nd:YAG diode pumped solid state laser (2)
- 270 mm Holographic Optical Element (HOE) scanner with 15° scan half angle capable of rotational speeds in excess of 2,000 RPM. (US Patent US 2015/0029571 A1 January 29, 2015) (3)
- Real time transmit LOS adjustment relative to receive LOS which compensates for scanner motion during pulse round trip time.
- High efficiency narrow bandpass filter reduces solar background noise.
- Transmit beam shaping optic optimizes illumination pattern on the ground.
- Nadir looking Ritchey – Chrétien telescope for collection of returned light
- Inertial navigation system (INS/GPS) including Inertial measurement unit (IMU) (4 and 5) provides precise LOS knowledge.
- High speed flash detector for precision laser pulse timing
- Data acquisition electronics (6)
- Sensor controller

In operation, when the laser (2) fires, a flash detector triggers the TOF timers within the camera (1). The pulse, meanwhile, is deflected through the central transmit prism which has been adjusted (i.e., “clocked”) to compensate for the motion of receive field of view during the two way transit time of the laser pulse. The return pulse is collected by the Palmer scanner (3), passes through the narrow bandpass filter to reduce the amount of solar background, then to the 128x32 GmAPD camera (1). The measured TOF and metadata values are then passed to the processing subsystem via the data acquisition subsystem (6) which combines the camera TOF data with all the metadata required for creating point cloud data as well as system health and status data. The associated line of sight orientation and sensor position data is determined by the IMU (4) via the INS/GPS (5).

Given the ability of a GmAPD detector to measure a single photon, minimizing solar background is an important consideration during the design of the system. The choice of system wavelength has a significant impact on the solar background level and overall system efficiency. For example, a LiDAR using silicon based detectors with a frequency doubled Nd:YAG laser operating at a wavelength of 532 nm is subject to three times the solar irradiance when compared to a Nd:YAG LiDAR system operating at a wavelength of 1064 nm. In addition, the 1064 nm Nd:YAG laser is
approximately twice as efficient as the frequency doubled Nd:YAG laser. Other effective methods of reducing solar background is minimizing the system aperture, installation of a narrow bandpass filter in the receive path, reducing the detector instantaneous field of view (IFOV), minimizing the range gate duration, or by simply operating at night [2]. By designing and operating the system such that solar background is minimized significantly increases data quality while increasing the operating range of the sensor and reducing or eliminating the need for noise filtering.

Collection Geometry

The Harris Geiger-mode LiDAR sensor uses a conical Palmer scan pattern produced by a direct drive, hub driven HOE scanner. HOE scanners have been used in the past [15] but this particular implementation has several advantages over previous designs:

- High power transmit beam is steered by fused silica transmit prism (1) while low power return signal is collected by holographic optical element (2) eliminating chance of damage to holographic element.
- The mechanical axes of the transmit prism (1) and receive holographic element (2) are coaxial and rotated by the same direct drive motor.
- Transmit prism diameter determined by out-going laser beam diameter only (doesn’t scale with receive aperture).
- Uses smaller diameter bearings compared to perimeter driven scanners, reducing drag and weight and increasing reliability.
- Scales to apertures > 300 mm and scan rates of up to 6,000
- Simple mechanical, electrical and control direct drive system design with few moving parts.
- Transmit LOS clocking mechanism (3)
- Leverages COTS components, minimizing custom parts
- Low power consumption

The estimated nominal design range of practical scan half angles is 10° to 45° determined by available laser power which ultimately limits the maximum scan angle for any given altitude and sample density. The current system uses a scan half angle of 15° which, when flying at 6 kilometers above ground level, the resultant swath width is 3.2 kilometers wide. Assuming a platform speed of 440 kilometers per hour (240 kts) yields an instantaneous area collection rate of 1,050 square kilometers per hour. The sensor also has automated range gate delay control as well as multi-pulse in flight discrimination logic.

When flown with 50 percent overlap, the scan pattern provides four looks from four different directions. With a scan half angle of 15° the sides as well as roofs of structures is sampled, which significantly increases the interpretability of the point cloud data.

![Figure 8. Direct drive, hub driven, holographic optical element scanner](http://proceedings.spiedigitallibrary.org/)

![Figure 10. Palmer scan pattern with 50% overlap provides four independent views of the scene](http://proceedings.spiedigitallibrary.org/)
Sensor Performance

The system is capable of imaging a 10% Lambertian target at a spatial sample density of 2 points per square meter at an altitude of 6 km during the day in an urban aerosol environment with 5 km visibility. When operated at night in a rural aerosol environment with 23 km visibility the operating altitude is increased to 8 km (Figure 11).

![Graph showing altitude and area coverage rate versus sample density](image)

**Figure 11.** Altitude and area coverage rate versus sample density

Example Imagery

Some examples of imagery from the initial flight tests are shown in Figure 12. Sample density and range precision support the collection of USGS Quality Level 1 data (8 pts/m²) at an altitude of 6 km and Quality Level 2 (2 pts/m²) at 8 km and above.

![Imagery examples](image)

**Figure 12.** Imagery of San Diego CA, single pass from 17 kft
4. SUMMARY

Over the past decade and a half, several imaging LiDAR sensors based on Geiger-mode avalanche photodiode (GmAPD) arrays have been successfully flown providing the technical foundation for a commercial mapping Geiger-mode LiDAR system. The commercial availability of high PRF, high pulse energy lasers and large format GmAPD cameras now make the construction of a commercial Geiger-mode LiDAR system economically viable.

REFERENCES


