A new photon-counting lidar system for vegetation analysis

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Abstract

This paper considers the potential of a new scanning photon-counting system for vegetation analysis. The 3D Mapper sensor was developed by Sigma Space Corporation and is being tested within NASA's Carbon Monitoring System (CMS) project (NASA, 2010). The sensor is able to map 60 km^2 per hour using less than 150 mW of 532 nm green light with about 30 cm between measurement points. While this area coverage rate is already several orders of magnitude higher than can be achieved by conventional lidar, substitution of higher power lasers would permit significantly higher mapping rates with the same resolution or much higher spatial resolution at the current rates. Data were collected for a test site to the west of Fredericksburg, Virginia, USA and demonstrated the capability with a low powered laser, of relatively high density data collection, and good penetration through the canopy, despite high canopy fractional cover and a hazy atmosphere at the time of flight. This preliminary study supports the potential of this emerging technology for vegetation analysis. Further research is required to develop algorithms to exploit the capabilities of such systems and to provide a greater understanding of the interactions with vegetated surfaces. Studies of this nature will inform future photon-counting satellite lidar sensors such as NASA's ICESat II, which is due for launch at the beginning of 2016.

Keywords: Photon-counting, green wavelength, ambient noise, signal detection algorithms, Carbon Monitoring System (CMS)

1. Introduction

1.1. NASA's Carbon Monitoring System project

This research is being carried out within the context of NASA's Carbon Monitoring System (CMS) initiative (NASA, 2010; Suárez *et al.*, submitted this edition). One component of CMS is the local-scale mapping of biomass using datasets which are expected to be readily available within the US (these include the US Geological Survey National Land Cover Data (NLCD) and lidar data). The aim is to determine a methodology for county-level analysis which could be extended and applied at regional, State or national scales. Since photon-counting lidar data offers prospects for future large area mapping for vegetation analysis, the potential of such sensors is being considered as part of this project. Further details of the CMS initiative are presented in Suárez *et al.*, submitted this edition.

1.2. Photon-counting lidar systems

The emerging technology of photon-counting lidar offers the potential for low energy expenditure and potential high altitude operation allowing extended laser lifetime and large area coverage. This newest type of lidar technology is currently generally operated at green wavelengths (532 nm). For some airborne systems, this is due to a greater efficiency of the detector and in the case of NASA's ICESat II, it is as a result of technical readiness for space flight.

Low laser energy output ensures eye safety of these instruments despite operating at a visible wavelength. A high pulse repetition rate and photon detection probability produces a high point density even whilst flying at greater altitudes whilst a narrow pulse duration (<1ns) allows photons to be located with greater vertical precision.

One significant factor resulting from the green wavelength is that photons returned from the emitted pulse cannot be distinguished from detected photons resulting from ambient noise. A small detector field of view and narrow optical band-pass filter are two important elements to reducing the background noise as much as possible. Much of the remaining background can be eliminated by coincidence filtering. Acquiring data at dusk or night would further reduce the background noise.

1.2.1. Micro-Altimeter

To date, few photon-counting systems have been developed and perhaps among the earliest of these was the Micro-Altimeter which flew several times in early 2001. It was a four channel, conical scanning instrument with a 7 to 20 mW micro-chip laser. The system produced profiles and terrain maps from 6 to 12 km including through heavy fog and under shallow bays (Degnan *et al.*, 2001). Some further examples of profiling and scanning photon-counting lidar systems, from both airborne and spaceborne platform are outlined below.

1.2.2. SIMPL

The Slope Imagining Multi-polarisation Photon-counting Lidar (SIMPL) is an example of an airborne small footprint photon-counting profiling lidar which operates at both 1064nm and 532nm wavelengths (Dabney *et al.*, 2010). A single pulse is emitted which is split into four beams, each with four channels for green and NIR wavelengths each of which at parallel and perpendicular polarisations. The two polarisations respectively identify photons which have been reflected from a single surface or which have undergone multiple scattering. The four beams are distanced approximately 5 metres apart, producing four profile 'slices' through the canopy. The laser repetition rate of 11.4kHz and an aircraft speed of 100m/second may be expected to produce 5-15 detected pulses per square metre.

Using SIMPL, Harding *et al.*, in press 2011, have explored the influence of lidar wavelength on the ability to determine standard waveform metrics which may be employed to predict biomass. By aggregating detected photons over a distance along the transect, the authors calculated a cumulative height distribution (such as that used for waveform or discrete return analysis). Height of median energy (HOME) and canopy cover metrics were compared and little difference was found between the two wavelengths, suggesting that lidars using 532nm could produce comparable biomass estimates to those obtained by current 1064nm systems.

1.2.3. ICESatII and MABEL

NASA's forthcoming ICESat II mission is due for launch in early 2016 (GSFC, 2011a). In contrast to ICESat I, its successor will carry a medium footprint, photon-counting profiling lidar operating at 532nm wavelength. This instrument is named ATLAS, the Advanced Topographic Laser Altimeter System.

The current planned configuration is for a single emitted pulse which is split into six beams, arranged as three adjacent pairs. Each pair will have a stronger and a weaker beam (100µJ and 25µJ respectively) which aims to address issues of detector dynamic range when alternating between bright and dark surfaces such as ice and water. A distance of 3.3km is anticipated between each pair and members of the pair will be separated by 90m. The high repetition rate of 10 kHz from an altitude of ~496km will produce overlapping footprints of 10m diameter which will be distanced at 0.7m intervals.

1-3 photons are anticipated to be detected per footprint and, although the spatial location of photons within the footprint will be unknown, the aggregation of returns along the ground tracks will allow a vertical profile to be created. Like its predecessor, the primary objective of ICESat II is not the retrieval of vegetation, one of its science objectives is measuring vegetation height as a basis for estimating large-scale biomass and biomass change (GSFC, 2011a). This new technology will offer a new perspective of the world and open opportunities for different approaches to global vegetation analysis.

Prospects for data collection in preparation of ICESat II are being tested using NASA's high-altitude simulator, the Multiple Altimeter Beam Experimental Lidar, MABEL (GSFC, 2011b). MABEL is a demonstrator instrument for the ICESat II mission, flying above the atmosphere at an altitude of 20km on NASA's ER-2 aircraft. It has been flown in December 2010 and again in March-April 2011 at different times of day, producing different levels of solar background which can be used to test signal detection algorithms. Data have been made available online by NASA at GSFC, 2011b.

1.2.4. Sigma Space 3D Mapper

For the study presented in this paper, the prototype 3D Mapper photon-counting, scanning lidar developed by Sigma Space Corporation, USA, is being tested to assess the potential of this sensor for vegetation analysis within the context of NASA's Carbon Monitoring System initiative (NASA, 2010).

The instrument measures approximately 60 km^2/ hour with 30 cm postings using about 150 mW of green light, emitting a 532nm, 0.7ns (700 picosecond) laser pulse at a repetition rate of 20 kHz. A 10x10 array of beamlets is produced on the ground and two time-of-flight cards, each with 50 channels, record the data collected. Photomultipliers were selected as the detectors for this system because of their very fast recovery time. The short system dead time, about 1.6 ns, means that each channel is armed and ready for the next event within 20 cm of a previous detection. This permits high resolution vertical mapping of forest canopies. The system uses 532 nm light because the detector has much higher quantum efficiency for green light than for the infrared. The green may have an additional advantage for vegetation measurements in that the lower reflectivity (relative to IR) significantly reduces multiple scattering and so improves the measurement fidelity.

Scanning patterns using this prototype instrument can be conical or near-linear. For a conical scanning pattern, the half-width angle is typically 9°, producing up to a 3-second difference between forward and backward views of the same location on the ground. For this study, a near-linear scan was used at a 45° angle to the flight path producing a swath width of approximately 300m.

2. Data collection

A test site at Fredericksburg, Virginia, USA was flown on 12th May, 2011, using the 3D Mapper photon-counting sensor. The data presented were acquired during a single pass flying at circa 280 km/hour at an altitude of 1km. This prototype system, in this mode, can capture data over 6,000 hectares per hour. Flight time was at 3pm, meaning that the sun angle and atmospheric haze observed during the flight produced challenging conditions to test the performance and capabilities of the instrument.

The site is located at a distance of 15 km to the west of Fredericksburg, and approximately 80 km SSW of Washington DC. The area contains predominately deciduous forest shown in lighter green in Figure 1 (below), of mixed height composition and density as well as residential and retail land use. The transect used for illustration of the sensor capabilities below crosses an area of evergreen (coniferous) forest with dense canopy cover (darker green, figure 1, below).

Figure 1. Test site near Fredericksburg, Virgina, USA. Above: GoogleMaps image with a 800m section outlined in red; Below: National Land Cover Data (US Geological Survey). Mid green represents deciduous forest; evergreen forest is indicated in darker green, light green is mixed forest, pale pink is developed/open space, and beige is shrub/scrub. Some misclassification can be observed which would have implications for biomass mapping using this dataset for stratification of the landscape.

3. Initial observations and results

The area illustrated within Figure 2 is 800 metres across and shows a horizontal breadth through the canopy of 10 metres. The tree canopy and ground are clearly visible against the solar background above and below. At times, haze prevented visibility to the ground surface, however, even under these conditions, adequate signal photons were received to enable the ground and canopy surfaces to be differentiated from background noise.

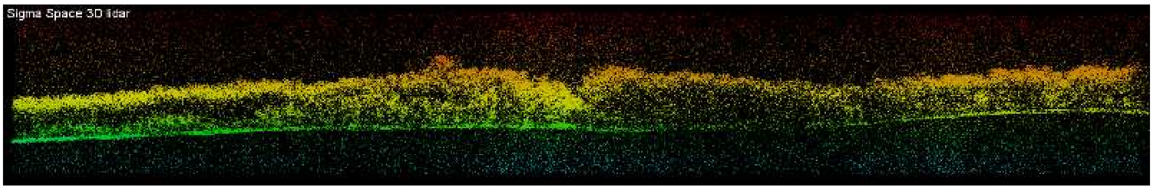


Figure 2. Illustration of vertical profile showing signal and noise above and below the intercepted surfaces.

Figure 3 shows a close-up view of the vegetation canopy. Emergent and suppressed crowns can be visually identified. This suggests the potential for methods to be developed to distinguish understorey vegetation beneath an upper canopy.

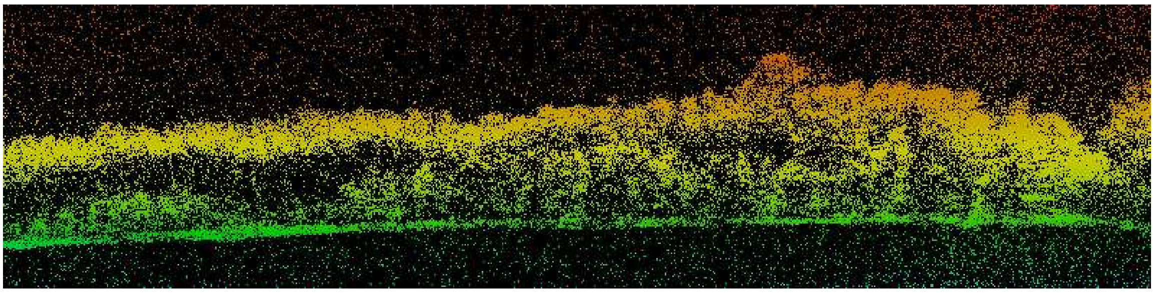


Figure 3. Observation of understorey vegetation beneath a dense canopy.

4. Next steps

4.1. Research flights

A research-focused photon-counting lidar campaign is planned during Summer 2011 over the Jug Bay Wetlands Sanctuary (Jug_Bay, 2011). This is an area largely of mixed broadleaf forest, located approximately 32km to the southeast of Washington DC. Field data were collected between 2003 and 2005 by a team of volunteers of the Wetland Sanctuary, for 300 10x10m plots arranged at 100m intervals on the UTM 18N grid. Discrete return lidar data were also acquired across this area of Maryland State in 2004. Additionally, some further field measurements were taken in 2011 as part of NASA's CMS project (NASA, 2010; Suárez *et al.*, submitted this edition).

This will enable a comparison of photon-counting data with field measurements as well as conventional discrete return lidar data. The time difference in lidar data collection along with repeat field measurements would allow growth to be observed and will assist in the assessment of biomass mapping as part of the CMS project.

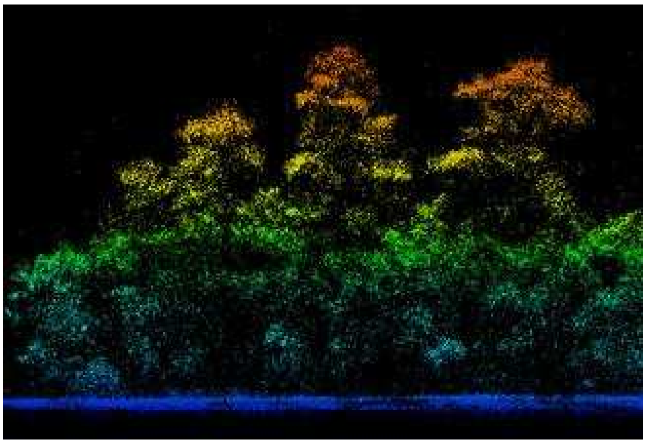
5. Discussion

5.1. Capabilities and potential applications

Initial tests suggest that promising results may be obtained from small footprint photon-counting sensors for the generation of vegetation products. The high density of the point cloud which is produced, in excess of that which is typically collected by discrete return airborne lidar data, aims to improve the characterisation of vegetation canopies and offers the opportunity for established analysis techniques to be applied to this new technology.

The potential to maintain a high detection rate of photons from a high altitude, could reduce data acquisition costs and permit more economical inventory and mapping of broad areas. The observation of understorey vegetation (Hill, 2007), which is difficult to achieve using more conventional lidar systems, could improve the capabilities of identifying invasive species and accounting for over-reached trees in canopy metric-based statistical equations for biomass mapping. This also presents the opportunity for improvements in the detection of small and suppressed trees using individual tree-level lidar inventories (Suárez, 2010).

A greater number of returned photons are observed for more reflective surfaces (e.g. painted lines on roads) and so changes to photon density could offer the possibility of direct crown-width detection in open canopies by observations of shadowing effects on the ground. Additionally, data acquisition during leaf- off conditions, and the improved vertical precision anticipated from the short duration pulse, may reveal potential applications for forestry such as timber quality (number and location of branches and tree architecture) seen in figure 4.



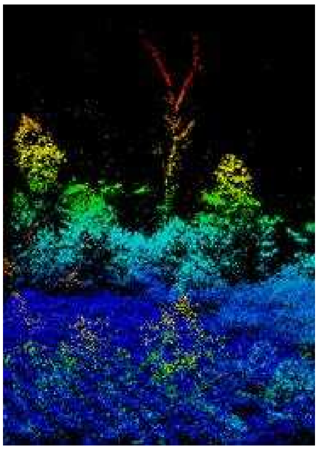


Figure 4. Canopy profile and branch architecture from an earlier test flight at the Smithsonian Environmental Research Center (SERC), Maryland, USA using the Sigma Space prototype photon-counting sensor.

5.2. Challenges of green wavelength photon-counting

The principal challenge of emerging photon-counting systems at green wavelengths is the ability to distinguish signal from noise. Photons returned from an intercepted surface cannot be differentiated from those originating from ambient noise and, whilst for planar surfaces such as roofs and bare earth, these can be classified reasonably easily, vegetation will require more careful consideration.

This is likely to be particularly important when identifying rough-surfaced transition zones such as the top of canopy. Additionally, noise photons cannot be discriminated within the canopy region and therefore adaptations to percentile-based methods of statistical analysis will be required, which take into account the random but uniformly-distributed photons beyond the true intercepted surfaces in order to adjust for spatially-varying ambient noise.

5.3. Prospects for photon-counting lidar

NASA's ICESat II mission is planned to be a green-wavelength, photon-counting, profiling system (GSFC, 2011a). As the only currently-planned satellite lidar sensor, the subject of ambient noise and the development of canopy/ ground-finding algorithms are issues which will need to be addressed. Data from MABEL (GSFC, 2011b) gathered at an altitude of ~20,000 km aboard the NASA ER-2 aircraft are providing an opportunity to develop algorithms in advance of the launch of the satellite. Possible future high-altitude airborne scanning photon-counting systems producing wider swaths would improve capabilities to map at landscape scales. For example a next generation version of the 3D Mapper flying at an altitude of 5-7000 km could cover circa 25,000 hectares per hour.

Research using the FLIGHT and DART lidar simulation models (North, 1996; North *et al.*, 2010) aims to further inform the understanding of photon-counting lidar and their interactions with vegetation canopies. As a newly-emerging technology this will be subject to ongoing research and evaluation to extract the full potential and to develop new methods to process data which aim to offer new capabilities.

6. Conclusion

This paper has illustrated preliminary results of a test flight at Fredericksburg, Maryland, USA, using the Sigma Space prototype 3D Mapper photon-counting system. Initial findings suggest great promise can be offered by such systems for vegetation analysis which may improve current capabilities offered by discrete return lidar systems. Further work is required to address issues of ambient noise and to determine characteristics of photon interactions with the canopy. A lidar campaign is planned for Summer 2011 over the Jug Bay Wetlands Sanctuary which will permit more in-depth analysis of the prospects of green-wavelength, photon-counting lidar for forest assessment.

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References

Dabney, P., Harding, D., Abshire, J., Huss, T., Jodor, G., Machan, R., Marzouk, J., Rush, K., Seas, A., Shuman, C., Sun, X., Valett, S., Vasilyev, A., Yu, A. and Zheng, Y., 2010. The Slope Imaging Multi-polarization Photon-counting Lidar: development and performance results, IEEE International Geoscience and Remote Sensing Symposium, 11686732, DOI 10.1109/IGARSS.2010.5650862, pp. 253-256.

Degnan, J., McGarry, J., Zagwodzki, T., Dabney, P., Geiger, J., Chabot, R., Steggerda, C., Marzouk, J. and A., C., 2001. Design and performance of an airborne multikilohertz, photon-counting microlaser altimeter. International Archives of Phorogrammetry and Remote Sensing, XXXIV - 3/ W4: 9-16. Annapolis, MD, 22-14 Oct. 2001.

GSFC, 2011a. ICESat-2. Available online at: http://icesat.gsfc.nasa.gov/icesat2/index.php.

GSFC, 2011b. ICESat 2 - MABEL simulator. Available online at: http://icesat.gsfc.nasa.gov/icesat2/mabel.php.

Harding, D., Dabney, P. and Valett, S., in press 2011. Polarmetric, two-color, photon-counting laser altimeter measurements of forest canopy structure, SPIE Proceedings LIDAR and RADAR 2011, Nanjing, China.

Hill, R.A., 2007. Going Undercover: Mapping Woodland Understorey from Leaf-On and Leaf-Off Lidar Data. In: P. Rönnholm, H. Hyyppä and J. Hyyppä (Editors), Proceedings of the ISPRS Workshop 'Laser Scanning 2007 and SilviLaser 2007'. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Espoo, Finland.

Jug_Bay, 2011. Jug Bay Wetlands Sanctuary. Available online at: http://www.jugbay.org/ Accessed June 2011.

NASA, 2010. NASA Carbon Monitoring System Initiative. Available online at: http://cce.nasa.gov/cce/cms/index.html.

North, P.R.J., 1996. Three-Dimensional Forest Light Interaction Model Using a Monte Carlo Method. IEEE Transactions on Geoscience and Remote Sensing, 34(4): 946-956.

North, P.R.J., Rosette, J.A.B., Suárez, J.C. and Los, S.O., 2010. A Monte Carlo radiative transfer model of satellite waveform lidar. International Journal of Remote Sensing 31(5): 1343-1358.

Suárez, J., Pinto, N., Rosette, J., Fatoyinbo, T.E., Nelson, R., Dubayah, R. and Cook, B., submitted this edition. A Carbon Monitoring System (CMS) for US counties using Airborne LiDAR Data.

Suárez, J.C., 2010. An Analysis of the Consequences of Stand Variability in Sitka Spruce Plantations in Britain using a combination of airborne LiDAR analysis and models, PhD, University of Sheffield, Sheffield, 295 pp.