How did we get here? An early history of forestry lidar

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Abstract. Functioning lasers were first demonstrated in 1960 in the United States and in 1961 in Canada and in the Soviet Union, but research into the use of lasers as forest measurement tools did not begin for another 15 years. Initially, with respect to Earth resources, lasers were employed to measure sea ice surface roughness, to make near-shore bathymetric measurements, to penetrate forests to make detailed topographic measurements, and to fluoresce oceanic phytoplankton for surface current studies. Some of these early studies noted that forest profiles were evident but in fact added noise to topographic retrievals. As early as 1964, researchers noted vegetation returns acquired using an airborne helium–neon (He–Ne), 0.63 μm, continuous wave (CW) laser. A decade and many airborne studies later, scientists with TRANARG, a mapping and surveying company in Caracas, Venezuela, reported on flights undertaken in 1976 that utilized a He–Ne lidar to collect over 11 000 km of lidar profiles, spaced 1.5 km apart, to construct a topographic map to help site a new reservoir. Though they depended on the laser to penetrate vegetation, they noted 35–40 m median canopy heights with emergents up to 55 m in their profiles. Trees came to be regarded as a signal rather than noise in the mid-1970s. In 1976 in the Soviet Union, Russian researchers felled a birch and a spruce, aimed a He–Ne CW laser with a spot size of approximately 25 mm at the horizontal trees, produced a profilograph, compared it with tape measurements, and concluded that, with increased power, such a laser could be mounted on an aircraft to remotely measure forest canopies. In 1979, they mounted their He–Ne laser on an AN-2 biplane and acquired their first airborne profiles. These studies and others done prior to 1985, i.e., the first two decades of airborne laser research, are reviewed in this glance backwards at the history of forestry lidar.

Résumé. Les premiers lasers ont vu le jour en 1960 aux États-Unis et en 1961 au Canada et en l’Union Soviétique, mais les recherches portant sur l’utilisation des lasers comme instruments pour faire des mesures forestières n’ont débuté que 15 ans plus tard. En ce qui concerne l’étude des ressources terrestres, les lasers ont d’abord été utilisés pour mesurer la rugosité de la surface des glaces marines, faire des mesures bathymétriques à proximité des côtes, pénétrer au travers de la végétation afin d’obtenir des mesures topographiques détaillées sous couvert forestier, et aussi pour étudier les courants de surface en mesurant la fluorescence du phytoplancton océanique. Si certaines de ces études font déjà mention de profils de végétation forestière bien apparents, ces profils sont considérés comme source de bruit additionnel lors de l’extraction d’informations topographiques. Dès 1964, des chercheurs ont ainsi observé des retours liés à la végétation dans des données acquises en utilisant un laser à hélium–néon (He–Ne) aéroporté, laser à onde continue (CW « continuous wave ») et émettant à 0.63 μm. Une décennie et de nombreuses études basées sur des mesures aéroportées plus tard, des scientifiques, en collaboration avec TRANARG, une société de Caracas, au Venezuela, spécialisée dans la cartographie et les levés topographiques, ont rendu compte de survols réalisés en 1976 en utilisant un lidar à He–Ne pour collecter plus de 11 000 km de profils lidar espacés de 1.5 km afin de produire une carte topographique dans le cadre d’un projet d’implantation d’un nouveau réservoir d’eau. Bien qu’attendant avant tout du laser qu’il pénètre au travers de la végétation pour pouvoir décrire le terrain, ils ont relevé sur leurs profils des hauteurs médianes de canopée de 35–40 m, avec des émergents atteignant 55 m. Le signal lié aux arbres a commencé à être considéré comme une information et non plus comme du bruit au milieu des années 1970. En 1976, en l’Union Soviétique, des chercheurs russes ont abattu un bouleau et un épicéa, ont pointé en direction des arbres couchés un laser He–Ne continu avec une taille d’empreinte de ~25 mm, l’ont utilisé comme un profilographe et ont ensuite comparé les résultats avec des mesures prises avec un mètre. Ils concluent que, en augmentant sa puissance, un tel laser pourrait être embarqué dans un avion pour mesurer la canopée forestière. En 1979, ils embarquèrent leur laser He–Ne sur un biplan AN-2 et firent l’acquisition de leurs premiers profils aéroportés. Ces études, ainsi que d’autres études réalisées avant 1985, et donc au cours des deux premières décennies de recherches sur les lasers aéroportés, sont passées en revue dans cette rétrospective de l’histoire du lidar en forsterie.
Introduction

The science associated with the use of airborne and space lasers to measure vegetation is well established, but the origins and underpinnings of forestry lidar science now reach back almost 50 years. Many of the documents that describe these initial airborne lidar studies and experiments sit in old symposium proceedings on library shelves, in company archives, or in government technical memoranda. Language also impedes access, and translations of early Russian journal articles, for instance, can be expensive, time consuming, and difficult to understand if the translator is not well versed in the arcana of lidar remote sensing.

These types of documents are reviewed to try to determine, for instance, who first looked at a vegetation profile generated by a laser? Who first related laser ranges to forest structure? What challenges did the early researchers face? What were the primary applications of the first airborne lidar systems? What kinds of lasers were used to acquire the measurements? The steps, the gains in knowledge, that have carried us to where we are today have been incremental and have accumulated over five decades. This paper looks at the first two decades of the documentation of the development of lidar, lasers, their integration onto aircraft, and research undertaken by these laser and lidar pioneers. The results of their early efforts lead directly to our present capabilities, capabilities that currently permit us to measure directly or to estimate the biophysical characteristics of forests in great detail.

The context of this early work is important because the politics of the 1950s, 1960s, and 1970s set the tenor for much of the research done in the United States (US). The microwave equivalent of the laser, the maser (microwave amplification by stimulated emission of radiation), was developed and made operational in the 1950s. Attempts to build the first operational laser (light amplification) were made in the late 1950s, with success realized in 1960. Much of the research was conducted in the US, in Canada, and in Russia, which at the time was part of the Union of Soviet Socialist Republics (USSR). The Iron Curtain separating the Communist east from west and the language barrier dictated that much of the formative work to make the world’s first laser proceeded independently. Though politically the US and the USSR were bitter enemies, there was cross-talk, cooperation, and visits between Russian and US scientists who were trying to develop the hardware to amplify microwaves and light waves to produce coherent, spectrally pure, powerful beams of electromagnetic radiation (C.H. Townes, personal communication, 2012). In addition, things that we take for granted today did not exist then. Early computers were as large as rooms; today’s scientific calculators have more RAM than the computer aboard Apollo 11, the first manned mission to the Moon. Digital recording devices (e.g., magnetic tapes invented 1951 and hard drives first used commercially in 1956), were large, limited, and cumbersome. The first Global Positioning System (GPS) satellite was launched in 1978, the full complement of 24 orbiting GPS satellites was completed in 1993, and the US Department of Defense did not stop intentionally degrading the accuracy of the civilian GPS signals until 2000. The Russian equivalent, GLONASS (Globalnaya Navigatsionnaya Sputnikovaya Sistema or Global Navigation Satellite System), became available to the civilian sector in 2007. Functional lasers, transportable computers to record laser data, and geolocation information were not as readily accessible nor as easy to use in the “early days” of forestry lidar.

Development of the laser

Numerous researchers working independently in the USSR, Canada, and the US developed the idea of “stimulated emissions of radiation” (the “ser” in laser), working first with microwave amplification (masers, early 1950s) and then with light amplification. In 1955, Aleksandr Prokhorov and Nicholay Basov, working with microwaves in the USSR, determined that optical pumping could be used to maintain continuous, stimulated emissions. In the US the patent for the laser, at that time called an “optical maser”, was filed in 1958 by Charles Townes and Arthur Schawlow of Bell Labs, was awarded in 1960, and was contested in court until 1987. The person contesting the Bell Labs patent, Gordon Gould, a PhD candidate at Columbia University in 1958, coined the term “laser” in a paper presented a year later (Gould, 1959). Though subject to some debate and litigation, the contest to build the first operational laser was won by the Hughes Research Lab in Malibu, California, on 16 May 1960. Theodore Maiman assembled and operated a pulsed, synthetic ruby 0.694 μm (red) laser (Maiman, 1960), besting others at Bell Labs, Columbia University, and at the Technical Research Group, a US defense contractor. The first laser, an instrument that can easily be held in the palm of an adult hand, was capable of firing only a single pulse. The inventor of that first laser described it as being a one “Gillette” instrument because it could only burn through one Gillette razor blade. The world’s first laser still works, as demonstrated on its 50th birthday in 2010 at Simon Fraser University in Vancouver, British Columbia, (http://spie.org/x40717.xml [accessed 8 February 2013]).

Canada fired its first laser on 12 January 1961 at the National Research Council’s (NRC) Sussex Drive spectroscopy lab in Ottawa, Ontario. Boris Stoicheff and Alex Szabo built the laser but were having problems with the...
purity of the ruby crystals; their instrument would not fire. Arthur Schawlow, working at Bell Labs in Murray Hill, New Jersey, visited the pair at the NRC. When told of the problem, he pulled a ruby rod out of his pocket and offered it to the Canadian team. The substitution worked (Szabo, 2010).

Behind the Iron Curtain, independent developments in laser design were in progress, well documented in a collection of papers, freely downloadable with English translations, made available by the Russian Academy of Science in 2010 (http://www.opticsinfobase.org /laserfest/ laserfest-soviet.cfm [accessed 8 February 2013]). The first Russian laser, also made of ruby, was operated successfully in June of 1961 at the Vavilov State Optical Institute in Leningrad (Belousova, 2011), now called St. Petersburg.

In the west, public reaction to the invention of the laser was somewhat varied. While today lasers are ubiquitous – CD/DVD readers/writers; surveying instruments; range finders for docking, agriculture, and forestry; fiber-optic data transmission systems; security devices; firearm sights; manufacturing; cameras; retail checkout counters – in the early 1960s the preliminary response was that Maiman's laser was a solution in search of a problem (Townes, 2003). Others prognosticated sophisticated, hideous new weaponry; Maiman was dismayed at initial news reports that characterized his invention as a death ray. Despite the hyperbole of these early news reports, the international community acknowledged the contributions of scientists on both sides of the Iron Curtain. Charles H. Townes (US), Nikolay Basov and Aleksandr Prokhorov (USSR) were jointly awarded the 1964 Nobel Prize in Physics for their research (http://www.nobelprize.org/nobel_prizes/physics/laureates/1964/press.html [accessed 8 February 2013]) which led to the development of masers and lasers. Dr. Maiman was twice nominated for the Nobel Prize but was never awarded the honor.

The first lasers were single-shot instruments; the flashlamp would excite the medium, initially a ruby crystal, and the laser would immediately emit one short pulse of coherent light. Continuously operating lasers were quickly developed. Within 7 months of Maiman's ruby laser demonstration, Ali Javen, William Bennett, and Donald Herriot of Bell Labs developed the Helium–Neon (He–Ne) gas laser, the first laser to generate a continuous beam of coherent light. This continuous wave (CW) laser, first operated in December 1960, emitted an orange or red beam at 0.633 μm. By 1961, lasers were being sold commercially by such companies as Spectra-Physics and Perkin-Elmer. The field took off, with researchers worldwide exploring different lasing media, excitation methods, power capabilities, and beam control procedures. A concise timeline of the research that fundamentally affected the development of the vast array of lasers is available at http://www.photonics.com/Article.aspx?AID=42279 [accessed 7 February 2013].

Early lidar work in the natural resources

Initially, with respect to Earth resources, lasers were used (i) to measure range from aircraft to target and (ii) to induce fluorescence in a variety of targets. Early lasers deployed to assess natural resources were used to measure sea ice surface roughness (Ketchum, 1971; Li et al., 1973; Tooma and Tucker, 1973; Hibler, 1975), to make near-shore bathymetric measurements (Hickman and Hogg, 1969; Hoge and Swift, 1979; Hoge et al., 1980), to penetrate forests to make detailed topographic measurements (Krabbil et al., 1980; Arp et al., 1982), to fluoresce oceanic phytoplankton for surface current studies (Hoge and Swift, 1981, 1983), to delineate ocean oil spills (Hoge and Swift, 1980), and to fluoresce terrestrial vegetation (Hoge et al., 1983). Many of these early studies employed CW lasers such as a 0.633 μm He–Ne laser. Pulsed lasers began to come to the fore in the late 1970s and early 80s, though one of the first bathymetric studies by Hickman and Hogg (1969) utilized a pulsed neon, 0.540 μm, gas laser with a controllable pulse repetition rate of between 1 and 100 pulses per second to estimate water depth in turbid waters of Lake Ontario down to 8 m (26 ft). Link and Collins (1981) wrote a summary article that (i) explained differences between pulsed and CW systems, (ii) provided options to measure aircraft position and attitude, and (iii) detailed current (i.e., 1981) applications e.g., water quality studies that depended on Raman backscatter and fluorescence and ranging studies for bathymetry and terrain mapping. As late as 1981 in the US, trees were considered to be a source of noise rather than as a target of opportunity because vegetation was regarded as a landscape feature that needed to be mathematically removed or, at a minimum, occasionally penetrated to characterize topography.

The use of CW lasers by early researchers stand in marked contrast to the pulsed laser systems that predominate today. Today's systems measure the time of flight of individual pulses to targets, frequently recording multiple returns (a multistop system) or continuous returns (waveforms) as a given pulse progresses through a diffuse target such as a tree canopy to the ground (Lefsky et al., 2002; Lim et al., 2003). CW lasers retrieve ranging information not by measuring time of flight of laser pulses or individual photons, but rather by measuring phase differences between the transmitted, continuous beam of laser light and the continuously received return beam. Light can be characterized as a sine wave and coherent laser light as a sine wave of a given wavelength, frequency, and amplitude. CW systems retrieve distance by looking at wave offsets or phase differences, and these wave offsets can be directly related to a distance from, for instance, aircraft to target. Necessarily then, these early CW systems acted as first-return systems, i.e., ranging data was available only to the first target intercepted by the beam.

Much of the early work in the US was driven by the Department of Defense whose research interests centered on topics that might help them advance or defend the interests of the US. Laser research projects characterizing sea ice
thickness, the location and height of pressure ridges, and ice extent were tied to US ventures under the northern polar ice cap (e.g., the nuclear submarines Nautilus, Skate, and Seadragon forays to the North Pole, 1958–1962) and subsequent Arctic deployments. Ocean circulation patterns were of interest to the US Navy as was ocean wave height determination. Remote sensing of oil spills, both in water and on land, was given some impetus by the building of the Trans-Alaska Pipeline (1974–1977). Interest and funding in bathymetry was, in part, tied to the Vietnam War (ca. 1964–1975) and the need to map navigable near-shore waters.

The first mention of an airborne laser profiler found by this author is reported in the proceedings of a symposium held at the University of Michigan in 1964. Rempel and Parker (1964) assembled and tested a Spectra-Physics 0.633 μm He–Ne CW gas laser coupled to a barometric sensor (to establish aircraft elevation) and to a nadir-looking photogrammetric strip camera to record flight line targets. They did this because the radar profilers in use at the time were relatively inaccurate, exhibiting errors of approximately 1 foot ± 0.5% (30 cm ± 0.5%) of the flight altitude. They flew their airborne laser profiling system in an Aero Commander at various altitudes, e.g., 280 ft (85 m) and 600 ft (183 m) above ground level (AGL). A very sensitive strip recorder, an oscillograph, which provides output visually similar to traces generated by seismographs, EKG strips, and lie-detectors, was used to record range to target (Y axis) as the plane progressed along the flight line (X axis). Unfortunately, this strip recorder overlaid a 0.6 inch (1.5 cm) high frequency signal atop the laser ranging measurements, so the traces illustrated in the Rempel and Parker (1964) manuscript are very coarse. Nevertheless, they concluded that, with numerous planned improvements, a one foot (30 cm) ranging accuracy was possible given a 10 foot (3 m) smoothing length from a flight altitude of 10,000 feet (3048 m) AGL. They also made first mention of possible forestry applications.

"The laser altimeter will be able to show ground elevations, as well as tree heights, if as little as 5 percent of the forest cover permits an optical path to the ground." (Rempel and Parker, 1964, pg. 327)

They also identified additional potential applications, e.g., sea ice studies, wave height determination (6 inch (15 cm) ranging accuracy), and road, railroad, and pipeline surveys. Petrie and Toth (2009) referred to Jensen and Ruddock (1965) as the developers of the first operational laser altimeter used for topographic mapping. It turns out that Rempel and Parker (1964), Jensen and Ruddock (1965), and Jensen (1967) all reported on different versions of the same airborne profiling system. Evidence for this can be found in the company names of the participants and also by comparing the perspective drawings of the airborne profiler (Figure 8 in Rempel and Parker (1964) and the drawing on page VIII-3 of Jensen (1967)). The profiles provided by Jensen (1967) are much cleaner; houses, trees, a cornfield with bushes adjacent, and an orange grove are similar to what we might see in a pulsed-laser profiler today. Obviously, they fixed their strip-recorder noise problem. 1965 was also the year that a lidar altimeter was demonstrated in the UK, measuring topographic elevations accurate to < 1.5 m at flying heights of 300 m AGL (Petrie and Toth, 2009).

Hickman and Hogg (1969) flew a high-powered, 0.540 μm wavelength pulsed neon gas laser with a 3 ns pulse width and an adjustable pulse repetition frequency (prf) of 1–100 pulses per second (pps) at 500 ft (152 m) over Lake Ontario at night to measure water depth. Soundings down to 26 ft (8 m) in relatively turbid water were noted, demonstrating "...the feasibility of an airborne bathymetric system for near-shore beach reconnaissance" (Hickman and Hogg, 1969, pg. 57). They also suggested that a high-rep-rate neon laser (1000 pps) could be adapted to an optical scanner to create a near-shore mapping system. It is interesting to note that they mounted their neon laser pitched forward 3 degrees to avoid specular reflection from the water surface, a technique employed in the ICESat-1/GLAS (Ice, Cloud, and Land Elevation Satellite/Geoscience Laser Altimeter System) design where the laser optical train was pitched forward 0.3 degrees to avoid specular reflection from water and ice surfaces (Neuenschwander et al., 2008). As a general rule of thumb, a 2 kW neon laser can penetrate the water column up to a depth approximately 3 times the Secchi depth; stronger lasers will go deeper (Link and Collins, 1981).

Link (1969) flew a He–Ne CW gas laser (λ = 0.633 μm) profiling system over 12 study areas, each 1600 ft along-track × 100 ft (488 m × 30 m), exhibiting a variety of terrain conditions that could affect military movements including ditches, spoil banks, roads, and vegetation. The laser was flown in conjunction with a barometric altitude sensor and a stereo camera system, and the flight profiles of terrain were compared with ground topographic surveys. The test sites were marked with cloth strips 6 in × 100 ft (15 cm × 30 m) laid out perpendicular to the flight path every 300 ft (91 m). The profiling data from the overflights, acquired in 1965 in a B-17 flying at 500 ft (152 m), were recorded on an oscillograph. Results indicated that the airborne laser profilometer could measure terrain features with a resolution of 0.3 ft vertical (9 cm) and 1.7 ft (52 cm) horizontal. He found that the system could not track the ground in vegetated areas and added that "This may be an advantage, however, if vegetation data are desired." (Link, 1969, pg. 191). He also noted that accurate terrain slopes over large distances were problematic (relative slopes over short distances were not) and identified the need for aircraft roll/pitch data and a more accurate aircraft altitude record.

Citing Australian Defence Scientific Service technical memoranda, Link and Collins (1981) reported that the Australians were actively engaged in airborne laser research and applications as early as 1970 (Penny, 1970, 1972). They used a CW argon laser (λ = 0.488 μm) profiler to collect
topographic transects to fill in gaps between reference elevations arrayed on a 97 km × 147 km grid across the entire country. The system depended on a barometric pressure sensor to track aircraft altitude and a strip camera to ascertain beam location. The utility of the system for topographic mapping was limited in areas with dense vegetation. Height measurement repeatability was judged to be 0.5 m in nonvegetated areas.

A number of ice studies were conducted in the early 1970s to map and measure sea ice characteristics. Ketchum (1971), reporting on flights in 1968 with a He–Ne CW laser over the Beaufort Sea north of Point Barrow, Alaska, attempted (i) to measure the height of sea ice ridges, (ii) to measure the horizontal extent of open water leads, (iii) to differentiate new ice, first-year ice, and multiyear ice, and (iv) to estimate ice thickness. Objectives i, ii, and iii were met, but ice thickness estimates were unacceptable because the variability in aircraft altitude readings precluded calculation of ice surface elevation above sea level. He noted that ice development, i.e., discriminating new, first-year, multiyear ice, was facilitated by recording laser return signal intensity. Ketchum (1971) posited that a uniform, common orientation of ice crystals in newly forming ice may specularly reflect the laser beam. He concluded that his ice profiler could statistically describe regional ice conditions with respect to ridge heights, ice development, and extent of water openings. Tooma and Tucker (1971) extended the work of Link (1969) and Ketchum (1971) to areas of sea ice north of Greenland. They compared laser heights to photogrammetric heights of ice features identifiable in both sets of data and found that laser values were consistently less than photo measures but consistently within 0.3 m.

In 1975, a hydrography workshop (Goodman, 1975) was held in Rockville, Maryland, bringing together a number of airborne lidar scientists and engineers to design a multi-purpose airborne laser profiler and scanning system for NASA. The new system was to be used for hydrographic ranging and to fluoresce oceanic phytoplankton, fluorescent dye (for fresh water and oceanic current studies), and terrestrial vegetation. The new airborne system would eventually become the Wallops Airborne Oceano- graphic Lidar (AOL) used by Krabill, Hoge, Swift, Maclean, Nelson, and others. The workshop is notable from three standpoints.

First, it laid down system requirements for various applications, requirements that demanded knowledge of both aircraft position and attitude. To accurately locate a given laser pulse on the ground, three, possibly four, factors need to be precisely measured simultaneously: (i) the position of the laser aircraft relative to some fixed geodetic coordinate system; (ii) the 3-axis attitude of the laser aircraft – roll, pitch, and yaw; (iii) the range to target, and (iv) the angle of the laser beam if the beam is scanned. The fourth factor need not be considered if a profiling lidar is locked in position, typically near-nadir, in the aircraft. Early studies were challenged by equipment limitations, e.g., Z control was coarse given dependence on barometric readings or radar altimeters, precise aircraft attitude information was often not available, and digital recording devices, if used at all, were new, bulky, and heavy. The 1975 workshop proceedings are the first mention that this author could find reporting the use of an inertial navigation system (INS) onboard an airborne laser platform. The workshop also called for operation of an airborne laser scanner with an adjustable prf up to 400 pps and an adjustable conical scan angle nominally fixed at 15° but which could be increased to 25°.

Second, the workshop highlighted the primary interests of the participants, those being near-shore bathymetry, Raman scattering, and fluorosensing.

Third, participants from the Canada Centre for Remote Sensing (CCRS) informed the workshop as to the progress that they had made in these research areas. A 1974 paper by John V. Watt (CCRS), which he presented at the 13th Annual Hydrographic Conference, was reprinted in the Goodman (1975) workshop proceedings on pages 13–24. That paper and the one that followed by John Bristow (CCRS), (pages 25–34 in Goodman (1975)), provided extensive details concerning the CCRS airborne laser system and work done with that system in Canada over the previous few years. As of 1974, CCRS listed their fluoroscensing–bathymetric lidar and Litton LTN-51 INS as “experimental” and a 14-track, high-speed, magnetic tape drive, a Doppler radar, various photogrammetric cameras, and 1 and 2 channel infrared imaging scanners as “operational”. CCRS interests included (i) remote sensing of laser Raman scattering to identify aquatic pollutants with an ultraviolet (UV, 0.337 um), pulsed (9 ns Full Width Half-Maximum (FWHM) nitrogen laser; (ii) fluorosensing with the UV laser to track aquatic oil pollution and chlorophyll–algal distributions; and (iii) laser bathymetry with a green (0.540 um) pulsed (3 ns FWHM) neon laser. In bathymetric mode, the pulse detectors aboard their aircraft, a DC-3, recorded multiple ranges per pulse, sensing both the water’s surface and the bottom.

In 1976, Nielsen and Aldred in the Forest Management Institute, Canadian Forest Service, went to an IUFR conference in Oslo and reported on efforts to better estimate timber volume in tropical forests (Nielsen and Aldred, 1976). They employed large-scale airphotos (1:500 up to 1:4000) to measure the top of the tropical canopy, a radar to measure the location of the ground beneath the canopy, and a barometric sensor to record aircraft or radar height above a datum (e.g., sea level). Their radar ground lines in the tropical environs were compromised by the dense vegetation, and they concluded that additional work was needed to improve their radar. They mentioned in passing that “Experiments with a laser altimeter... have been successful at providing stand profiles under Canadian conditions (Figure 9 in Nielsen and Aldred (1976)).” In a report two years later, Nielsen and Aldred (1978) provided details of an
Early lidar work measuring forests

While US researchers were concentrating on more aquatic pursuits and Canadians were measuring the tops of forest canopies with stereo photos and ground traces with radars, Soviet researchers started to look at the possibility of measuring trees with ranging lasers. Certainly tall grasses, shrubs, and trees had been noted in laser profiles prior to the Russian work, but in those cases, measurements of vegetation height and canopy structure were not the primary concern. Tree measurements became the primary objective rather than a source of noise in 1976 when, in the USSR, Solodukhin et al. (1976, 1977a) felled a birch and a spruce tree and aimed a He–Ne, 0.63 μm laser with a spot size of approximately 25 mm at the horizontal trees. They produced a profilograph, compared it with tape measurements, and concluded that, with increased power, such a laser could be mounted on an aircraft to remotely measure forest canopies. Later that year they mathematically explored the effects of random cross-sectional profiles through stands with differently shaped crowns (conic, parabolic, ellipsoidal–vertical, spherical, ellipsoidal–horizontal, and cylindrical) and deduced how different crown shapes affected laser profile height retrievals (Solodukhin et al., 1977b). They found that the arithmetic mean height of a stand of trees with conical crowns (e.g., spruce) was underestimated by 26.9%, whereas the mean height of larch stands, perhaps because of their more rounded crown, were underestimated by 8.1% (Table 2 in Solodukhin et al. (1977b)). Twenty years later, Nelson (1997), not realizing that Solodukhin et al. had already done the work, looked at the effects of canopy shape on height retrievals and found that average height as measured along a simulated lidar profile increased as canopy shape morphed from a cone to a parabola, an ellipsoid, and a sphere. Random transect measurements of parabolic crowns were 8% taller than conical canopies; spherical crowns produced profiles that were 26% taller than conical canopies.

Solodukhin et al. (1979) and Kuliasov et al. (1979) reported on their first efforts to fly their CW He–Ne laser on an AN-2 biplane and acquired their first profiles in September 1977. The mission was flown at 160 km/hr at 40 m AGL with the plane carrying the laser profiler, an oscillograph to record the profiling trace, and a “slit aerial camera”. A “leveling” (presumed photogrammetric) camera was flown over these same targets in November 1977. Their selected targets were all relatively short because their system, limited by the phase cycle, could not resolve heights > 15 m. The spot size at target was approximately 20 mm. They flew over a “desiccated” marsh (Lake Shirskoye, 65 km S of Leningrad), pine saplings and alder, and an abandoned brick factory (Figure 1). They reported differences between ground and airborne profiling lidar measurements of building heights of 2 to 7 cm. They also reported that the maximum error in determining ground elevation beneath a closed forest canopy of 40 cm with a root mean square error (RMSE) of 14 cm. Solodukhin et al. (1979, pg. 45) concluded that their laser system afforded a very accurate picture of forest canopy profiles and posited that such profiles “…may serve as the basis for the automated determination on a computer of the cost indices of timber stands…”.

A year later, Krabill et al. (1980) would report a 50 cm RMSE of the lidar profile relative to photogrammetric profiles in closed canopy situations. Over open ground, that RMSE dropped to 12 cm (Figure 9 in Krabill et al. (1980)). Perhaps more interesting was that Krabill et al. (1980) began their report with a description of the Wallops Flight Facility’s airborne laser scanner, the AOL, the offspring of the system designed by the participants in the 1975 Hydrography workshop (Goodman, 1975). The Krabill report listed the three primary uses of the profiling or scanning AOL as (i) an airborne bathometer, (ii) an airborne laser fluorosensing instrument, and (iii) a topographic mapper. Proposing a terrestrial application of its bathymetric capability, they noted that the AOL could be used to
measure tree heights. “In this application the tree canopy acts much as a water surface, reflecting a portion of the energy directly back to the aircraft while a part of the energy continues on to the forest floor to be reflected back to the aircraft.” (Krabill et al., 1980, pg. 2). The 1980 AOL instrument, housed in a C-54 Skymaster and later in a P-3, had onboard a computer and a magnetic tape drive to digitally record the ranging measurements from the 2 kW neon gas lidar (0.540 m) emitting up to 400 pps. It also had a Litton LTN-51 Inertial Navigation System providing real-time roll and pitch, a vertical accelerometer to better monitor aircraft elevation, and a photogrammetric camera that acquired sequential 9 inch × 9 inch color photos. Marking flight lines on the ground was still challenging, depending as always on cloth strips, weather balloons, and, at night, strobe lights. They reported that pilots could usually fly the marked line to within ±30 m. Data acquisition height for these 4-engine turboprops was typically 150–300 m AGL. Ground reference with respect to where the laser actually tracked was supplied by the coincident airphotos.

Two years later, in July 1982, tethered meteorological balloons and orange tarps were used to guide the Wallops P-3 onto a 14 km flight line that ran along a mountain ridge in south-central Pennsylvania near Doubling Gap (Nelson et al., 1984). The oak–hickory forests at the south end of this line had been, over the previous two months, completely defoliated by the gypsy moth (Lymantria dispar L.); canopy closure was near-zero. At the north end of the line, the hardwood forest had not suffered the gypsy moth outbreak and canopy closures were near 100%. The AOL, then currently configured with a nitrogen laser (λ = 0.337 μm) operating as a profiler, acquired ranging measurements at 400 hz. With an aircraft speed of 100 m/s, pulses were emitted every 0.25 m along-track. New electronics allowed the AOL to function as a truncated waveform system. After a preset, fixed delay, a 12 m vertical window opened and the system would record laser return intensities every 2 ns (30 cm) so that, in the post-processing phase, analysts could attempt to find a ground spike in the foreshortened waveform beneath the first return. Various lidar height and density metrics were compared with similar photointerpreted quantities derived from coincident stereo airphotos along 1 s (approx. 100 m) segments of the lidar profiles. Results were significant but relatively weak, e.g., laser versus photointerpreted density $R^2$ approximately 0.6. Variables that proved useful for predicting photointerpreted canopy density included (i) the proportion of pulses where a ground spike was identified in the waveform, and (ii) the cross-sectional area between the top-of-canopy and terrain along 1 s (approx. 100 m) segments. Tree heights measured on airphotos using a parallax bar were compared with lidar heights ($n = 15$). Lidar means were within 0.6 m of photointerpreted heights though the range of the photointerpreted heights
were twice the lidar ranges. As Krabill et al. (1984, pg. 693) concluded, at this point in time, “...the greatest remaining obstacle to the implementation of airborne lidar techniques to terrain profiling over forest-covered areas is the aspect of inflight navigation.” Airborne lasers provide accurate ranging data, but knowledge concerning the location and attitude of the aircraft calls into question the location of the laser’s ground trace. In short, pilots could not hit marked targets reliably ($\pm 30$ m) and analysts had to depend on airphotos to identify where the plane and laser beam tracked. Ground–laser comparisons were an exercise in approximation.

While many of the first laser systems were flying in large propeller-driven, 2- or 4-engine aircraft, McDonough et al. (1980) described an airborne laser profiling system designed for smaller aircraft such as a single-engine Cessna 206 or twin-engine Cessna 310. This all-digital system recorded (i) waveform measurements from a 10 Hz yttrium–aluminum–garnet (YAG) ($\lambda = 1.064$ $\mu$m, 0.532 $\mu$m frequency-doubled) profiling lidar; (ii) microwave ranges to 3 reference base stations to track aircraft $X$, $Y$ position every 2 s; (iii) barometric pressure for aircraft $Z$ control, and (iv) digital aircraft roll and pitch. They used a 35 mm boresighted camera to record the ground transect. In a nominal flight profile (915 m AGL, 216 km/hr (60 m/s)), the system illuminated a 3 m diameter spot on the ground every 6 m. Simulations indicated that the system would penetrate Costa Rican jungle canopies even when 99% of the incident pulses were occluded by green vegetation.

Schreier et al. (1984) reported on the latest version of a Canadian airborne profiling lidar system, previous versions of which had been flying, some in small aircraft, for almost 10 years. They used coincidently acquired stereo photos and ground surveys to assess the accuracy and precision of their 2000 Hz, gallium–arsenide, 0.904 $\mu$m, pulsed-laser profiles. System limitations were such that only every 5th pulse could be recorded, limiting their PRF to an effective rate of 400pps. They flew their system over the Petawawa National Forestry Institute outside of Chalk River, Ontario, and over a photogrammetric test site near Sudbury, Ontario. Calibration results indicated that (i) pulse locations beneath the DC-3 aircraft could wander as much as 30 m over a 10 s period due to aircraft attitude changes, i.e., variations in roll and pitch; (ii) laser-photo height differences on three flight lines were $-0.05 \pm 0.61$ m, $-0.24 \pm 0.64$ m, and $0.01 \pm 0.90$ m; (iii) 95% of all laser heights were within 1.8 m of photo heights; and (iv) laser profile versus ground survey comparisons indicated that the laser profiles were “…significantly more variable than the ground survey profile” on vegetated (grass, fern) surfaces, i.e., $33 \pm 23$ cm versus a sandy surface, $18 \pm 16$ cm. They also noted that if aircraft attitude changes are not taken into account, then laser-photo differences essentially doubled, i.e., with INS: $-0.24 \pm 0.64$ m versus without INS: $-0.49 \pm 1.12$ m, due solely to laser-photo co-registration inaccuracy. A year later Schreier et al. (1985), using the same lidar system, assessed the utility of normalized lidar height measurements, lidar mean reflectance (0.904 $\mu$m), and the lidar reflectance variability (%CV) to see if they could be used to differentiate simple land cover types, e.g., conifer, hardwood, mixedwood, muskeg, grass, and bare sand. They concluded that (i) conifers could be differentiated from hardwoods based on lidar reflectance and reflectance variability measures, and (ii) simple vegetation and terrain classifications could be computed and digitally input to a GIS by combining reflectance variables with height measures and location information from their INS.

Aldred and Bonner (1985), in addition to providing a succinct summary of early Canadian altimeter work both with radars and CW lasers, also reported a remarkably comprehensive set of results based on the use of two pulsed-laser systems. They retrieved waveforms using a 10 Hz neodimium-doped: yttrium–aluminum–garnet (Nd:YAG) laser ($\lambda = 1.064$ $\mu$m, also frequency-doubled to 0.532 $\mu$m) with selectable beam divergences. They also tested a “production”, or off-the-shelf, first-return, Nd:YAG laser with adjustable firing rates up to 320pps. Both were flown in areas in the general vicinity of Ottawa over conifer, hardwood, and mixedwood forests, suburban areas, swamps, open grasslands, fields, and rock outcrops, both leaf-on and leaf-off. Coincident stereo airphotos were used to locate laser measurements on the ground and to measure canopy heights and stand densities. They noted that the systematic underestimation of laser measurements of stand heights could be mitigated by increasing beam divergence and concluded that “pulsed laser technology” (i.e., waveform retrievals) could accurately measure stand heights within $\pm 4.1$ m at the 95% level of confidence. Crown cover density classes could be discerned, but softwood and (or) hardwood cover type discrimination was beyond the capability of the height and density measurements acquired by pulsed waveform lasers. They suggested that future work should consider the utility of airborne lidar measurements for volume and biomass estimation.

### Estimating forest volume and biomass

In 1984, Gordon Maclean published his University of Wisconsin Masters thesis (Maclean and Martin, 1984) in which he photogrammetrically measured forest canopy profiles (no lasers involved) and related these stereophoto profiles to timber volume (Figure 3 in Maclean and Martin (1984)). He concluded that although measurements of dbh and height on the ground would yield more accurate results, his canopy profile metrics accounted for a high percentage of the variation in logarithmically transformed timber volume. He also concluded that these profile-area versus log-volume relationships were species-specific. Over the next two years, working at Wallops Flight Facility in Virginia, Maclean and Krabill (1986) applied the same methodology to airborne lidar profiles and concluded that (i) airborne
profiles were linearly related to the volume, \( R^2 = 0.73 \), \( \text{RMSE} = 36.6 \text{ m}^3/\text{ha} \); (ii) an exponential model, i.e., \( \log(\text{volume}) = f(\text{airborne profiling lidar metrics}) \), met regression assumptions of homoskedasticity and normality better; and (iii) stratification by tree species improved volume estimates. Airborne lasers could be used to predict the amount of wood on the ground, and the area of the lidar profile along a segment of set length could be used to accurately estimate timber volume. Upon reflection, this relationship between profile area and volume is no surprise as, given a constant segment length, the average height of all first returns in a segment is equal to (profile area) divided by (segment length). Nelson et al. (1988a, 1988b), using profiling data acquired by the Wallops lidar over a southern pine forest in SW Georgia, extended this work to include the prediction of biomass and to assess the repeatability of near-coincident flight lines. Repeat estimates of volume, biomass, and lidar height measures were within 3.2%–6.1% on 3 different flight lines where separation distances varied from 15 to 60 m, on average.

Discussion – building on the past

Subsequent work by an international pool of talented scientists and engineers has added greatly to our knowledge base over the last 25 years. Huge technological and scientific gains have been made, facilitated by GPS and GLONASS geopositioning; better INS systems to keep track of the orientation and location of the laser aircraft during a data collection campaign; and smaller, faster computers and better digital recording devices to store the phenomenal data loads. Absolute geolocation accuracies of individual scanning laser shots are now typically less than 2 m without base stations and \( < 1 \text{ m} \) with local base stations within 50–60 km of the flight path. Multiple-return or waveform ranging data are now routinely collected on each pulse. CW lasers, effectively first-return systems, are long a thing of the past with respect to forestry lidar applications. Within the last decade, lidar engineers have overcome the problem of keeping track of multiple pulses in the air, and now prfs of some airborne laser scanning (ALS) systems exceed 350 kHz, a rate more than 3 orders of magnitude faster than the first pulsed-laser system (1–100 pps) employed by Hickman and Hogg (1969).

Today, the technology is such that the forestry-lidar community can digitally look at and measure an individual tree in submetre detail, either from above using ALS or from the ground using terrestrial laser scanners (TLS). ALS systems are now routinely used to collect stand level and regional wall-to-wall forest mensuration data for forest management in some countries, primarily in northern Europe (Næsset et al., 2004; Næsset, 2007). Recent work with high-resolution (> 10 shots/m²) multistop ALS systems in mature tropical forests indicate that evidence of forest disturbance – skid trails, small feeder roads hidden by the overstory – can be clearly identified and delineated by utilizing within-canopy density and height metrics to measure near-ground canopy closure (d’Oliveira et al., 2012). Preliminary studies suggest that such techniques may be employed to address REDD (Reducing Emissions from Deforestation and forest Degradation) issues related to identifying sites that have been selectively logged, a topic which, up to this point, has been difficult to address using optical data. Robust lidar-based statistical designs have been developed (Ståhl et al., 2011; Gregoire et al., 2011), validated (Ene et al., 2012), and refined (Ene et al., 2013). These designs integrate ground plot measurements with airborne lidar transect samples to provide large-area estimates of forest volume, biomass, and carbon (Wulder et al., 2012a). Airborne lidars are also being integrated (or at least considered for integration) into national forest inventory plans, especially in those states or countries that support extensive tracts of remote, inaccessible forest, e.g., Alaska (Andersen et al., 2011) and Canada (Wulder et al., 2012b). Waveform data from a space lidar, ICESat/GLAS, have been used to create global forest height maps (Lefsky, 2010; Simard et al., 2011; Los et al., 2012) and to make estimates of circumpolar boreal forest biomass (C. Neigh, personal communication, 2012) and circumtropical forest biomass (Saatchi et al., 2011).

Thanks in part to the efforts of early inventors, engineers, and researchers, the airborne lidar community may, at this juncture, consider itself a mature (i.e., operational) science. But from the standpoint of large-area inventory, challenges and opportunities still lie ahead. Among these is the continued development of robust, statistically defensible inventory designs that integrate ground plots with both wall-to-wall ALS data or sampled ALS or profiling data. First among these sources are ALS sampling variability (assuming the ALS is used as a sampling tool rather than to provide wall-to-wall coverage) and model error, i.e., the variance component associated with the variability of the coefficients of a model used to predict, for instance, volume or aboveground biomass. Other sources of error should be assessed to see if they merit inclusion in analytic variance expressions, e.g., allometric error, ground plot measurement error. Second, with respect to airborne lidar acquisitions, it would be most helpful to integrate existing thematic maps with forest measurements using profiling or ALS data such that inventory information stratified into land cover types can be generated in flight, “real-time”. Given the development of predictive equations before the flight mission, one can envision a software and hardware package that can literally inventory vast tracts “on-the-fly” such that the regional inventory is complete when or very soon after the laser aircraft lands after acquiring its last sample flight line. Third, robust estimators must be extended to include three-phase or three-stage designs that incorporate (i) space assets, (ii) airborne lidars flying beneath those space acquisitions, and (iii) ground plots. These space assets might provide wall-to-wall coverage of forest structure (e.g., space radars such...
as the ALOS/PALSAR L-band radar), or they may sample the landscape (e.g., the ICESat/GLAS waveform lidar or the planned ICESat-2 photon-counting, multibeam profiler, due to launch in 2016). At a minimum, these three-phase and three-stage designs should account for first-phase and first-stage sampling error, if any (for instance, the sampling variance associated with GLAS orbits), and all model variance components.

Fifty years ago, the forestry lidar community did not exist. We are where we are today because of the work of a relative few who toiled under challenging circumstances in many countries – Australia, Canada, Russia/USSR, the United Kingdom, the United States, and Venezuela – to investigate and eventually make operational a new technology – airborne lidar ranging. Their early work can be easily overlooked, for much of it rests in obscure reports resting on dusty shelves in government offices with acronyms associated with bureaucracies that no longer exist. It is this author’s hope that this publication fairly places credit where credit is due and that it provides a context for much of the initial airborne lidar research that was done between 1960 and 1985.

References


grapha (Recording the contour of a region with an airborne laser


