# AIRBORNE LIDAR MAPPING OF INVASIVE LAKE TROUT IN YELLOWSTONE LAKE

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**ABSTRACT**

In 1994 Invasive lake trout (*Salvelinus namaycush*) were discovered in Yellowstone Lake near the center of Yellowstone National Park. The large lake trout feeding on smaller cutthroat trout (*Oncorhynchus clarki bouvieri*) seriously threatens the existence of this native species and seriously alters the ecological balance in Yellowstone National Park. During the September 2004 spawning season, an airborne lidar was flown over Yellowstone Lake to locate pockets of spawning lake trout to aid in the effort of identifying and eradicating this invasive species from the lake. The lidar data were used to generate a map of lidar-located fish. This map led to the confirmed discovery of a previously unknown pocket of invasive lake trout in the remote Southeast Arm of the lake.

## 1. INTRODUCTION

Invasive lake trout (*Salvelinus namaycush*) were discovered in Yellowstone Lake in 1994 [1-3]. The source, date, and mechanism of the introduction of lake trout into Yellowstone Lake are unknown. Recent research using Sr:Ca ratios from fish otoliths as a natural chemical marker suggests that these fish were transferred from nearby Lewis Lake in about 1989 [4].

The fundamental problem associated with lake trout in Yellowstone Lake is that many species of piscivorous birds and mammals rely on the native Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*) as a primary protein source, but the cutthroat trout population is being rapidly reduced through predation by lake trout [1-7]. It has been estimated that each adult lake trout consumes more than 40 cutthroat trout annually [7]. Lake trout cannot replace cutthroat trout in the Yellowstone ecosystem because lake trout reside at much greater depth, reproduce in the lake, and have larger body sizes than cutthroat trout, which exist in shallow waters and spawn in adjoining rivers and streams.

Cutthroat trout spawning in rivers and streams near Yellowstone Lake provide a major protein source for many important avian and mammalian species. For example, reduction in the cutthroat trout population negatively affects pelicans, osprey, eagles, grizzly bears, and river otters [1-12]. The number of cutthroat trout migrating past Fishing Bridge over the Yellowstone River just north of Yellowstone Lake have declined from 1999 to 2004, accompanied by a corresponding reduction of bear activity; anglers have also experienced a declining catch from 2 fish/h in 1998 to 1 fish/h in 2004, 0.7 fish/h in 2005, 0.4 fish/h in 2006, and 0.6 fish/h in 2007 [5,6].

Aggressive gillnetting by the National Park Service removed more than 270,000 lake trout from 1994 to 2007 [5,6]. The reduction of catch per unit effort and average length of spawning lake trout during this period indicates that the gillnetting efforts are reducing the lake trout's impact on the Yellowstone cutthroat trout [5,6]. However, because lake trout still present a serious threat to the Yellowstone ecosystem, new methods of locating and eradicating this nonnative species are desirable.

## 2. AIRBORNE LIDAR EXPERIMENT

In September 2004 we conducted an experiment to explore the feasibility of using airborne lidar for mapping lake trout spawning areas in Yellowstone Lake. Airborne lidar has been shown to be effective for locating, profiling, and mapping fish schools and other biological features in the open ocean [13-15]. However, the technique had not previously been used in lakes.

Airborne lidar offers the possibility of surveying large areas in relatively small periods of time compared with boats. This is an advantage in this application because Yellowstone Lake covers 352 $km^2$ in east-central Yellowstone National Park, with 177 km of shoreline, at elevation 2376 m with mean depth of 42 m and maximum depth of 118 m.

Lake trout remain at depths that are beyond the reach of avian predators, mammalian predators, and airborne lidars during the entire year except for a several-week spawning period that occurs typically in late August to early October. During this short opportunity, National Park Service fisheries biologists focus their efforts on gillnetting, primarily in the West Thumb of Yellowstone Lake where the largest known lake trout population exists. The short lake trout spawning season makes it extremely difficult to explore for additional pockets of lake trout in other areas of the lake, making an airborne lidar survey of great potential value.

### 2.1 Yellowstone Lake Flights

Our Yellowstone Lake fish lidar experiment took place during 18-24 September 2004, during the peak of lake trout spawning season. The King Air aircraft used for these flights was based at Bozeman, Montana for the entire period, although fall snow storms allowed us to fly over the lake on only one day (21 September). As shown in Figure 1, we flew for several hours in both morning and afternoon, focusing attention on the shallow waters near the lake's edge.

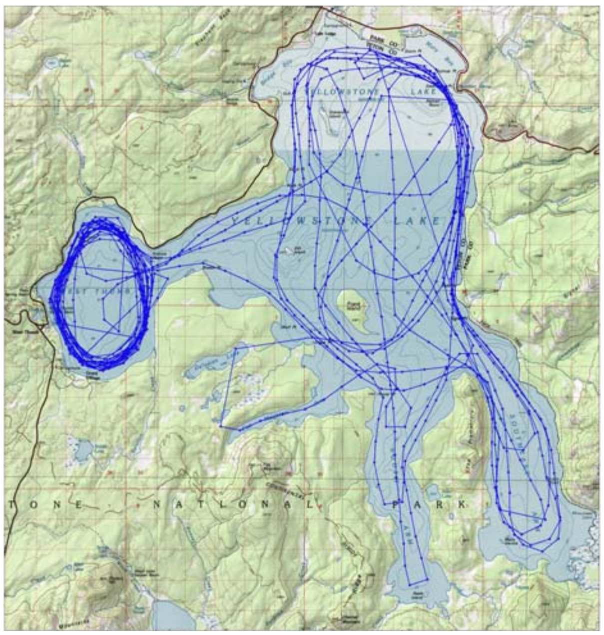


Figure 1. Airplane flight track over Yellowstone Lake on 21 September 2004 during the lake trout lidar experiment.

We flew many circles around the West Thumb where lake trout are known to exist in significant numbers, and also flew multiple times around the periphery of Yellowstone Lake to explore for yet unknown lake trout spawning areas.

### 2.2 Instrument Description

The lidar used in this study is a direct-detection, non-scanning instrument operating at a wavelength of 532 nm with nominally 100 mJ pulse energy and pulse repetition frequency of 30 pulses/s (see Table 1) [13]. The lidar records either co- or cross-polarized signals, but we collected mostly cross-polarized data because this offers greater contrast between fish and scattering from material in the water [13]. The beam is expanded to a diameter of at least 5 m at the surface to ensure eye safety for marine species [16]. Typical flight altitude is 300 m, but we flew a good portion of the Yellowstone Lake experiment at approximately 150 m.

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|---|---|
| Laser wavelength | 532 nm |
| Laser pulse energy | 100 mJ/pulse |
| Pulse repetition frequency | 30 pulses/s |
| Pulse width | ≤ 12 ns |
| Beam size | ~5 m at water surface |
| Receiver aperture | 15-cm diameter |
| Detector | Gated PMT |
| Receiver A/D converter | 8 bits at 1 Gsample/s |
| Signal preamplifier | Logarithmic |
| Analog bandwidth | 100 MHz |

Table 1. Characteristics of the airborne fish lidar.

The lidar was mounted in the back of the plane, pointed approximately 15° ahead of nadir through a hole in the floor, as shown in Figure 2. A rack of control electronics was situated in front of the optics head. The operator sat in a backward-facing passenger seat directly behind the co-pilot.

Figure 2. Lidar inside the airplane in September 2004. From left to right are backward-facing seats for lidar operator and observer, lidar electronics rack, and the lidar optics head looking through a hole in the airplane floor. (J. Shaw photo).

## 3. RESULTS

Automated algorithms exist that perform reasonably well with fish lidar data from the open ocean, but these algorithms often failed with the Yellowstone Lake data set because it included so many underwater objects. The results here were obtained by manually examining range-time profile images such as the one shown in Figure 3, where gray-scale lidar backscatter signals are plotted with range on the vertical and time (or flight distance) on the horizontal. Future applications of airborne lidar in situations like this will benefit greatly from advanced algorithm development.

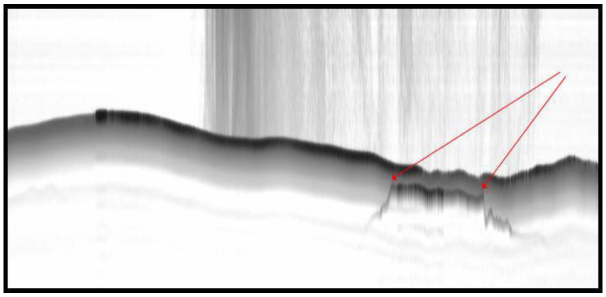

Figure 3. Time-height profile of airborne lidar data in the Southeast Arm of Yellowstone Lake. Arrows point to fish.

Figure 3 shows 500 lidar shots, covering 16.7 s or approximately 1 km. The water surface appears wavy because at this stage of processing the airplane's vertical motion has not been removed. Above the bright surface return is the air, which exhibits scattering from precipitation in this image. In this case, the precipitation is likely snow because of the significant level of scattered signal it produces in the cross-polarized data shown here.

Near the right-hand side of the image we found signals that indicate clumps of fish just above the edges of an underwater mesa. A close-up of this region of the image is shown in Figure 4. The fish scattering signatures are the vertically extended lines, caused by the temporal spread of the laser pulse, that appear to be floating between the solid underwater bottom and the water surface at the underwater cliff edges.

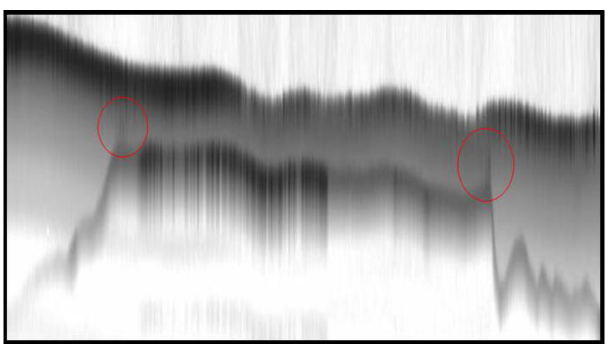

Figure 4. Zoomed-in range-time profile of airborne lidar data showing fish near underwater cliffs in the Southeast Arm of Yellowstone Lake. Circles indicate location of fish hits.

We visually examined each data image without any knowledge of its location to avoid biased opinions of where lake trout might appear. After recording a table of certain, likely, and possible fish hits, along with file name and corresponding lidar shot numbers, we then added the GPS coordinates to the data table and created a map showing the location of the likely and certain fish hits. This map is shown here as Figure 5, with red dots marking the "certain" fish hits and green dots marking the "likely" fish hits.

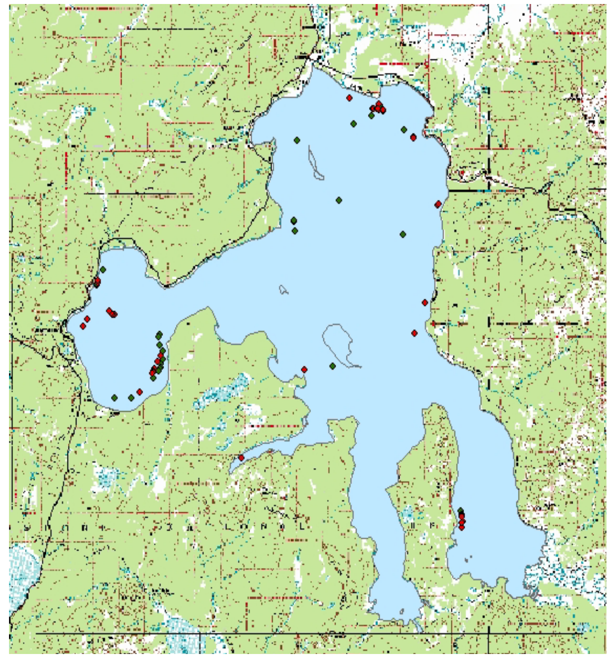

Figure 5. Map showing probable fish locations in Yellowstone Lake determined from airborne lidar data. Red dots indicate highest certainty and green dots indicate lower-probability fish locations.

The fish locations shown in Figure 5 include the well-known lake trout spawning areas in the West Thumb, plus a number of locations where lake trout were not known to exist at that time. In 2006 lake trout were also found just north of Snipe Point, south of the West Thumb on the western side of the lake. This discovery helped corroborate the lidar-generated fish map shown in Figure 5.

Lake trout are not known to exist in Mary Bay at the northeast corner of the lake, so those hits may either be cutthroat trout, some other object, or yet unknown lake trout. The lidar data do not directly indicate fish species, but we are exploring the possibility that the data may contain clues as to the fish species based on depth and spatial distribution compared with known fish behavior.

The Southeast Arm fish hits on Figure 5 are in a location where lake trout were not known to exist, but where models predicted they may. During the September 2007 lake trout spawning season, the National Park Service fisheries crew traveled to the Southeast Arm with gillnets to search for the fish that the lidar data indicated might be there. Figure 6 is a photograph of one of many lake trout, approximately 62-cm-long, caught with stomachs full of juvenile cutthroat trout of length less than 20 cm. This discovery of spawning lake trout served as an extremely valuable validation of the lidar-generated fish map.

Figure 6. Lake trout, caught in the Southeast Arm of Yellowstone Lake, had each eaten several juvenile cutthroat trout. These lake trout were found near the location indicated in the Southeast Arm on the lidar-generated map of Figure 5. (Stacey Sigler photo).

## 4. CONCLUSION

An airborne lidar was successfully used to map spawning lake trout in Yellowstone Lake. The map of probable lake trout spawning locations generated in this experiment led park biologists to a location in the remote Southeast Arm, where they found a thriving population of lake trout. Several of the lake trout caught had eaten multiple cutthroat trout, indicating the reality of the problem being addressed by this study. The success of finding lake trout leads to anticipation of future opportunities to employ this technology again in support of the Yellowstone ecosystem. Future research needs to address the need for improved data processing algorithms adapted to finding fish in a shallow near-shore lake environment.


## ACKNOWLEDGMENT

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