Clear Waters, Stronger Depths: Advancing Bathymetric Lidar Through Community Practices

Nicholas D. Johnson [1], Jennifer M. Wozencraft [1], Christopher L. Macon [1]

[1] Joint Airborne Lidar Bathymetry Technical Center of Expertise, US Army Corps of Engineers 7225 Stennis Airport Rd. Kiln, Mississippi – (Nicholas.d.johnson, Jennifer.m.wozencraft, Christopher.l.macon)@usace.army.mil

Keywords: Bathymetric Lidar, Laser Hydrography, Professional Practices, Collaborative Frameworks, Sensor Characterization

Abstract

The science of mapping beneath the water's surface with lasers is no longer novel, but its relevance has never been greater. Over the past decade, bathymetric lidar has evolved from a niche tool into a diverse ecosystem of sensors and operators, tailored to specific missions. This diversity brings strength but also challenges, requiring careful alignment of tools and tasks for meaningful results. Collaboration among academia, government, and industry has driven this evolution, exemplified by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX). Since 1998, JALBTCX has leveraged operational insights to elevate data quality and research for its partners. With the recent growth in technology and applications, industry have begun to look towards the American and International Society for Photogrammetry and Remote Sensing (ASPRS, ISPRS) for support in how they have improved our understanding in other remote sensing sciences. ASPRS's Bathymetric Working Group, inspired by the Multibeam Advisory Committee's wiki model, is fostering a centralized resource to address common challenges and approaches for specific applications. This paper presents a review of challenges that JALBTCX has experienced through decades of airborne lidar bathymetry operations, the foundational principles that govern them, and a framework and approach for maximum transparency in bathymetric lidar. "Clear waters, stronger depths" symbolizes a unified commitment to transparency, openness, and purpose-driven application, strengthening both our technical capabilities and collective trust in the maps we create.

1. Introduction

Bathymetric lidar's history starts quickly behind the development of a laser in 1960 with military research and testing in the 1960s and 1970s. Prototype foundational systems emerged in the 1980s, though they remained largely research focused until the 1990s, when operational systems from Canada, Australia and Sweden began being utilized by government agencies. Notably, Optech Inc.developed a bathymetric lidar system before introducing a commercial topographic sensor. The systems continued to evolve in the early 2000s, and the first "shallow" system was introduced by NASA and USGS using a shorter, less powerful laser pulse and narrower receiver field of view than other systems. Commercial companies providing services increased, and between 2010 and 2015 major manufacturers released new sensors in response to data-design needs. Over the past decade, sensor releases continue to diversify the tools and applications under the broader bathymetric lidar umbrella including miniaturized systems for UAS platforms, a push-broom imaging system, and NASA's ICESat-2.

The U.S. Army Corps of Engineers (USACE) developed the first operational airborne lidar bathymetry system in the U.S.A. in collaboration with the Canadian government and Optech. USACE began utilizing the technology in 1994 for navigation and coastal storm risk management projects and formed the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) with the Naval Oceanographic Office (NAVO) in 1998. The JALBTCX is a now collaborative partnership between USACE, NAVO, the National Oceanic and Atmospheric Administration (NOAA), and the United States Geological Survey (USGS) to advance bathymetric lidar through shared research, development, and operational interest.

JALBTCX has hosted an annual workshop since 1998, with attendance rising from around 25 people at the inaugural workshop to 100 participants in 2015 to 200 in recent years. ASPRS began offering an Airborne Bathymetric Lidar workshop at the GeoWeek conference in 2022 and were surprised to find attendance among the highest of the workshop offerings with increasing attention each year. ASPRS also formed a Bathy Working Group (BWG, 2025) under the lidar committee the same year to support best practices for a Federal Bathymetric Lidar Specification being developed at the time by JALBTCX. While bathymetric lidar presentations at geospatial conferences once fell under unique approaches or other catch-all sessions, it now regularly has multiple dedicated sessions. The widespread adoption of this technology, and services by an increasing number of practitioners, highlights its growing significance.

ASPRS and ISPRS share a common mission to advance the understanding and responsible application of geospatial technologies. In line with this mission and state of the practice, government practitioners, the expanding user base, industry and academia work through professional organizations to address the challenges posed by diverse systems, complex processes, and unique applications inherent to this rapidly evolving field. By fostering a shared vision, the bathymetric lidar community can continue to drive innovation and uphold the integrity of this transformative technology.

Gary Guenther, a pioneer in the field, offered invaluable insights that remain highly relevant today (Guenther, 1985). Guenther's work not only addressed the challenges then but also foresaw the complexities ahead, blending caution with excitement for the technology's future. Conclusions from three of Guenther's works will be used as a guide around experiences JALBTCX have faced. The "Airborne Laser Hydrography" report remains a cornerstone reference and, in the epilogue, Guenther states that the results of future systems are design and process dependent with the responsibility on the system manufacturer and survey professional to provide comprehensive solutions, with focus on four areas. "The four following examples are problem areas in which specific solutions will need to be carefully developed: propagation-induced bias correction, surface uncertainty, signal processing, and spurious responses. All are related to a single primary concern – depth measurement accuracy." (Guenther, 1985)

Guenther's advice following 15 years of continued research and data processing improvements expanded to emphasize how important survey management and processing tools were to the results. "Minimizing sensitivity to uncontrollable environmental effects while not introducing any uncorrectable errors" and "establishing procedures for limited manual interactions with the data" are two key conclusions to be discussed (Guenther, 2000). Guenther also supported the ASPRS Digital Elevation Model Technologies and Applications, 2nd Edition's chapter on bathymetric lidar which ASPRS has made publicly available through the BWG's community site (BWG, 2025). Guenther saw the future of commercial bathymetric lidar systems and services, left some gentle reminders to consider, and stated boldly "An ineffective or marginalized system is not a bargain and is not acceptable. Standards must be maintained, and lessons learned must not be forgotten." (Guenther, 2007)

The acoustic mapping practice has a research-led Ocean Mapping Community Wiki, advised by the National Science Foundation-funded Multibeam Advisory Committee (MAC, 2025), which is a collaborative space to share expertise with the aim of improving data quality for all. These are examples of mindsets and frameworks that support a similar technology and that ASPRS BWG is adopting. Practical guidance, open tools, best practices, top 10 common challenges, and links to external resources such as shared calibration test site data are all examples from the MAC wiki which the growing bathymetric lidar community needs.

This growing bathymetric lidar community consists of sensor manufacturers, survey practitioners, and data end users; and it needs a similar forum for openness and transparency on important topics that impact data quality and usefulness, with the intent to fuel improvements for all. This paper jump starts the discussion on three important challenges JALBTCX has experienced operating its own sensors and has encountered when evaluating data from other sensors. In other words, these challenges exist for all bathymetric lidar sensors to different degrees and have been addressed (or not) in several ways by sensor manufacturers and survey providers. End users need transparency on how these challenges are handled for each data set to ensure the data are suitable for their desired end use. Industry partners will remain anonymous as possible unless explicitly stated.

2. State of the Practice

For a couple of decades, government worked closely with industry on characterizing bathymetric lidar sensors in different environments, understanding associated biases, and designing data processing solutions that produced accurate data with few spurious returns. Guenther (1985) described the complexities related to errors with the statement:

> The error functionalities are entwined with system and environmental parameters such as scan angle, altitude, receiver field of view and optical bandwidth, transmitter pulse characteristics, pulse location algorithms, wind speed, and water clarity in a complex web which requires careful compromises in system design and operation to minimize the resulting errors.

In the past decade or so, sensor manufacturers have been bringing new sensors, or upgraded sensors, to market at a dizzying speed that does not allow for careful system characterization and elegant data processing solutions. New survey practitioners are entering the market to address the growing need for critical data in the coastal zone and along our rivers but may have little experience working in those environments or with bathymetric lidar. It is the responsibility of the data producer to understand these complexities with respect to the system, environment and desired product but it is ultimately the responsibility of the industry, including the users, to use the technology within reasonable limits. To accomplish that, we need a broad understanding of foundational concepts of bathymetric lidar and practical guidelines for implementation. From JALBTCX's experience, the three foundational concepts are propagation-induced depth biases, water surface importance, and signal processing.

2.1 Propagation-induced Bias Correction

The propagation-induced depth bias exists in all bathymetric lidar data, but is less significant in clear, shallow water. Because photons do not travel in a straight line from the sea surface to the seafloor but rather interact with water molecules and sediment particles along the way, with each interaction exaggerating the lengths of the paths the photons travel. So, depths measured by bathymetric lidar systems are deeper than actual depths. The deeper the water, the greater the exaggeration. The propagation-induced bias corrector is applied to correct this bias. Scattering and absorption of the attenuated pulse and the algorithms and methods to manage the ranging effects remains one of the most researched topics for bathymetric lidar and are detailed in (Guenther, 1985) and (Philpot, 2019). Two approaches are demonstrated below, a model-based depth-dependent corrector, and an empirically derived multiplier.

The first approach applies a depth-dependent lookup table of correctors based on propagation-induced bias modelling to measured water depths. The correctors were developed prior to fielding of a system but produced depths "free of dependencies" (Guenther, 2000) on depth, nadir angle, or water optical properties (Guenther, 2000) when compared to ground truth data. Ground truth comparison from two calibration sites, both acoustic references at Lake Erie or South Florida Testing Facility-SFTF Fort Lauderdale, had a normal distribution of differences as seen in Figure 1 from a 2010 calibration report.

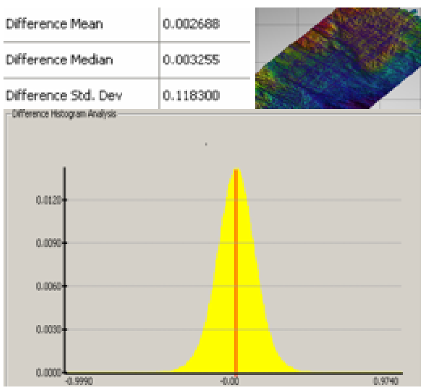

Figure 1. 2010 lidar versus reference difference histogram

The next sensor tested at JALBTCX took over a year to finalize software and processes such that a ground truth comparison would be meaningful. One such error in this sensor was a simple transposition error on a significant digit of the index of refraction for which the user chooses a programmed fresh, brackish, or salt option This sensor initially had depth bias results shown in Figure 2 like the two percent of depth errors reported with the Larsen 500 sensor (Hare, 1994).

Figure 2 plots all the lidar differences, green points, compared to the reference data with a moving average difference in red and two times deviation of the differences plus the moving mean difference in dashed lines. The blue lines represent the systems target vertical accuracy – uncertainty of 30cm with 1.3 percent of depth allowance.

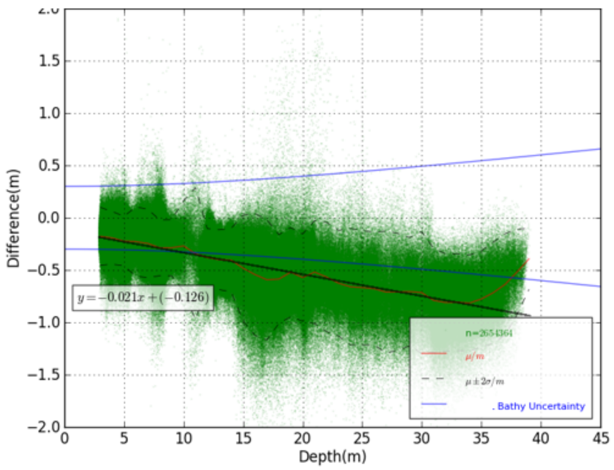

Figure 2. Difference between ground truth and calibrated lidar data not corrected for propagation-induced depth bias as a function of depth.

For this system, the manufacturer recommends use of depth scaling corrections for the linear portion of the difference to the reference data observed, and the software has a solution for managing the correction from the surface to the depth of where the linear correction was derived for non-linear system responses in shallow waters. Recommendations from this manufacturer are in line with another manufacturers guidance where these corrections when applied in moderately clear waters (Kd between $0.1m^{-1}$ and $0.2m^{-1}$) result in data within the designed specifications, where Kd is the diffuse attenuation coefficient representing how light diminishes in water with depth. Recommendations for very clear waters (Kd 0.05 m^{-1}) or very dirty turbid waters (Kd 0.4 m^{-1}) are to evaluate the depth bias in those regimes. JALBTCX finds, like (Wright, 2016), a constant range offset dependent on the receiver field of view (FOV) but one must also take caution in calibration not to misplace any other timing or ranging bias that may belong to other ranging corrections in air or the water surface. The depth scaling of these multi-receiver FOV system setups are typically similar between the different received FOV for this system. The depth scale here does depend on the interest point algorithms which the user can choose between two methods. Between generations of this system, JALBTCX finds a scale of 0.995 of the range in water in moderately clear waters for the interest point algorithm chosen.

JALBTCX partners continue to evaluate sensors and algorithms against our reference site in Florida as well as cross validating at other reference sites as described in the USGS report on depth calibrations for the EAARL-B sensor (Wright, 2016). The study found a FOV dependent range bias and a near two percent depth scale correction needed. Future work listed studying the calibration site for stability, assessing the biases in "non-clear water," and possible calibration coefficients on calculated optimal properties from the waveform. The conclusions and recommendations on sensor evaluations from Wright (2016) and Hare (1994) were also similar with considerations for temporal differences between datasets and natural variance in the seafloor, as well as questioning the uncertainty in the reference data itself. The USGS report does state the use of 1.333 for index of refraction, pure water, which would account for a third of the depth error reported if processed with values for a saline environment. The depth scale correction of the EAARL-B if processed with 1.343 for index of refraction would be closer to 0.987 where the JALBTCX system processed in the latest software using central peak detection needs 0.989. Dietrich(2025) and Schwarz (2021) reference Wright (2016), and the contribution of such processing errors that could exist as well as proposed practices or even possible solutions to the remaining portion of the depth bias.

JALBTCX continues the update and use of a reference site for changes to hardware and software finding it possible to utilize past corrections if the systems and peak detection algorithms are the same. Figure3 illustrates that the depth bias has been removed and the mean plus twice the deviation of the differences remains below the target uncertainty. Missing depth ranges are where slopes above three percent have been removed to take out effects related to horizontal uncertainties leaving flat regions between the reefs for vertical difference as done with the EAARL-B evaluation.

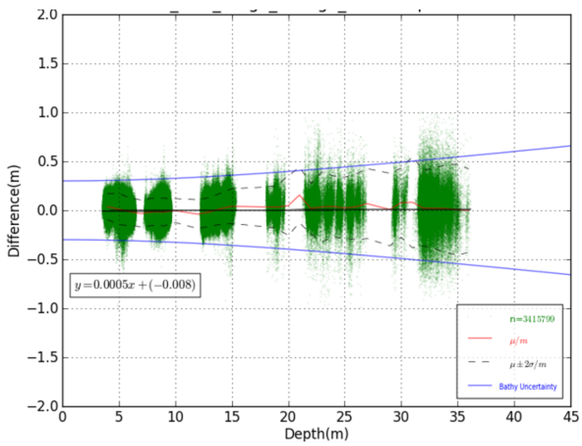

Figure 3. Difference between ground truth and calibrated lidar data corrected for propagation-induced depth bias as a function of depth.

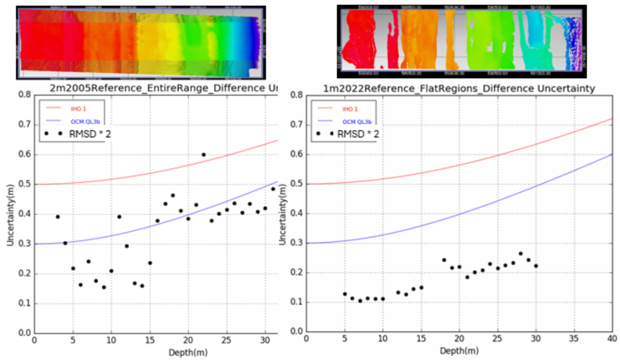

Figure 4. Calibrated lidar-reference RMS differences times two utilizing different reference surfaces

Figure4 shows differences of the lidar measurements to reference, taking the root mean square of the differences for each meter of depth and multiplying by two for a 95% check along with the plotted system design and IHO order 1 specifications in blue and red. The same 2024 lidar data used in differencing were from two flights consisting of three lines which have 60% overlap and are flown reciprocally for 200% coverage for a total of twelve lines. This allows for calibration of angular misalignments like a patch test for multibeam but also gives redundancy for variation in navigation and environmental influences. The surface and plots on the left includes the entire range with slopes and is made up from a dozen calibrated lidar flights from 2005 compiled to a 2 m mean surface. The surface and plots on the right is the range without slopes and is made up from three calibrated lidar flights from 2022 compiled to a 1 m mean surface. Twice the magnitude of error can be seen between the comparisons and often reports provide a single difference mean and deviation value for an entire area not considering slope-variation effects, as done in topographic lidar practices, or displaying the depth dependency. These processes have been validated against the USACE Field Research Facilities highly controlled acoustic and GPS profiles taken in Duck, NC. Some comparisons with other technologies have been done assuming all the error is in the data being analysed but as multibeam found single beam errors, lidar has "brought to light" errors in other survey methods (Guenther, 2000). Redundancy in survey practices remains necessary and are standard practice in geospatial standards and guidelines.

In absence of a well-calibrated system, with a robust propagation-induced bias depth correction, depth biases only become apparent with comparison to ground truth. JALBTCX have had contracted data delivered with these depth bias issues since before 2010. An interesting one to observe is in an area surveyed four times, twice by two different sensors, with depth bias issues between them. Each collect from a single sensor relatively agrees with its previous collect but there remains a three percent of depth difference between the two systems. Figure 5 shows the vertical Sections for sensor A and sensor B. Metadata reports RMSE less than 10 cm compared to RTK check points in wading depths of sensor B where depth differences are often noted negligible being within the uncertainty of water surface and navigation error sources. Standard practices for depth bias removal over a validated reference site would have prevented this issue. Figure 5 is a profile through 16 m of depth range where each sensor aligns with itself but there is 0.5 m difference between them at 16 m.

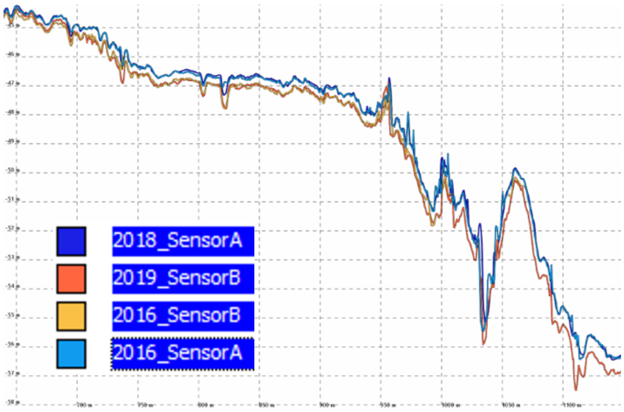

Figure 5. Profile illustrating differences between systems in an area surveyed multiple times

The confusion in the practice for depth biases have been found as recently as 2024 when JALBTCX partners were evaluating upgrades for a system, not previously mentioned, as well as contracting for collection with a calibrated version of the same system. One JALBTCX partner found the system measuring 50 cm above the reference data in 30 m of water using the default depth bias scale settings of 0.96 and needed to apply the recommended depth scale of 0.98 for clearer waters to correct the bias at the reference site in Florida. The other partner observed in the same model system processed using the 0.98 depth scale correction, data that measured 15 cm below the Florida reference in 10-15 m of water but then a trend back towards the reference to align near 30 m of water.

Another concern with the practice of these calibrations is that these scaling biases are typically derived from linear functions where the behaviour of the attenuation of light and often hardware configuration for managing the dynamic range of the signals received are non-linear processes. The algorithms and responses in processing vary from system to system. Figure 6 shows this system's depth difference with 0.98 depth scaling applied for the second system example. The moving average of differences per meter in the red line indicates the system growing away, deeper, from the reference from 5-15 m then trending in the opposite direction beyond 20 m. JALBTCX partners are still investigating the system and processes.

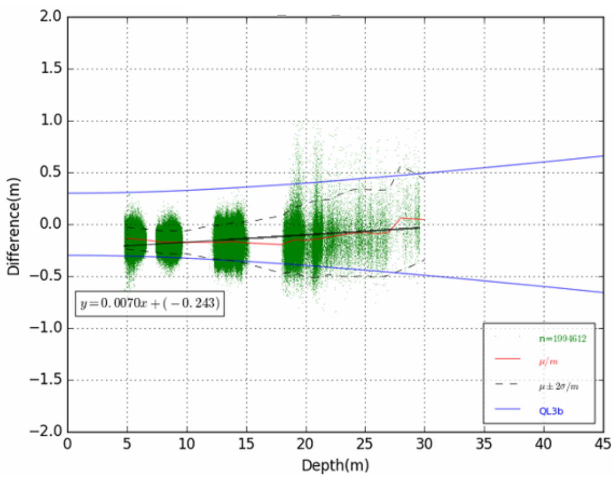

Figure 6. difference between ground truth and lidar data where the linear depth correction applied leaves systematic biases

https://doi.org/10.5194/isprs-archives-XLVIII-2-W10-2025-139-2025 | © Author(s) 2025. CC BY 4.0 License.

2.2 Water Surface Uncertainty

Academia and practitioners of bathymetric lidar are very familiar with the importance of the water surface with "surface" found 272 times in Guenter (1985) and 385 times in Philpot (2019), nearly always referring to the water surface. These references describe the complexities and dependencies, and the topic remains one of the major research topics in the field. The surface return energy from a green laser pulse is a combination of surface reflection and the backscatter from below the surface and the uncertainty of the position of the surface depends on the system design, environment, and algorithms used in processing. The accuracy of a bathymetric return depends on accurately knowing how much time light spent in air and how much time it spends in water. This problem "will have to be solved before a system meeting international accuracy standards can be fielded." (Guenter, 1985). "For this reason, a system with only a green receiver is unacceptable for hydrography." (Guenther, 2000) Generations of systems came after the one Guenther worked on that included three co-located surface return channels from which acceptable strategies to manage the environmental limitations and trade-offs of each to produce the best surface return per laser pulse were devised. Sensor manufacturers continue to improve their hardware and software strategies and two known at the time of writing are working on sensors with co-located IR and green pulses again after over a decade of abandoning this approach. Such a complex problem with a range of evolving systems and solutions can be hard to keep up with for those in the practice.

ASPRS and JALBTCX supported this effort with community input when creating the bathy domain profile for LAS files in 2013 by making classifications for water surface - class 41 and derived or synthetic water surface - class 42. Nearly all systems utilize some form of a modelled water surface to overcome the per pulse surface detection challenge. These models are either used directly as a synthetic surface, or to validate per pulse surface return, or a combination for the two. Data producers, as with the depth bias, often find their own solutions. These surfaces often come from a separate IR sensor with independent angular, intensity, and surface range bias uncertainties. Modelled surfaces in this case have a spatio-temporal disconnect from the green laser which could be up to two seconds apart depending on the scan patterns of each system.

Modelled water surfaces can introduce error into bathymetric lidar depth measurements, especially in the presence of large waves. These errors can cause dataset statistics to exceed accuracy requirements and introduce noise into the final delivered point cloud that obscures small features that may be of interest to the customer. Figure 7 are profiles through an area with 3.5 m wave heights processed with the systems surface detection logic on the top profile and a synthetic averaged surface on the bottom profile. In other words, this is the same data processed with different approaches to applying surface measurements. The profiles are taken across a single line with the red-orange points being the front scan and the blue line being the back scan. If a system were to operate in this environment and the surface was not captured requiring processes to average another source of data for surface location, there could be up to 40 cm of error in places as the profile shows 80cm between the scans in two places.

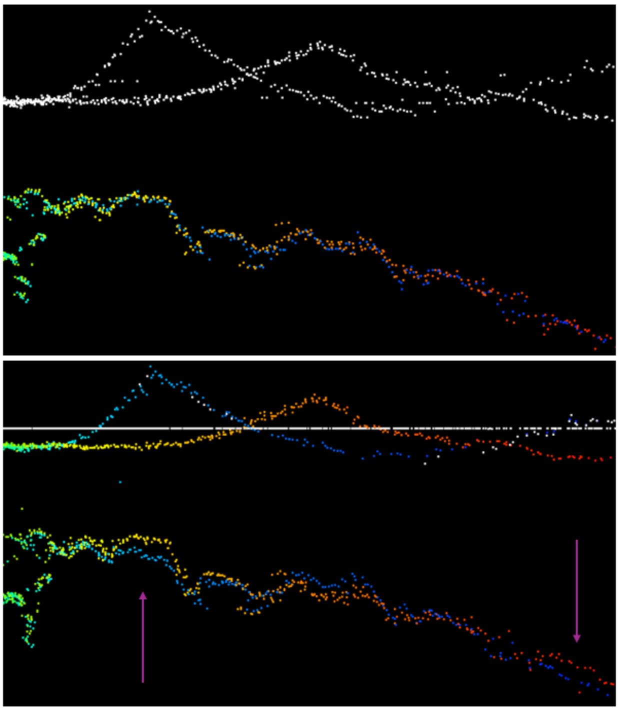

Figure 7. Lidar profiles coloured by scan direction. Top profile processed with a detected surface and the bottom profile processed with a synthetic average surface to show an 80cm between scans for if a system or process missed the surface.

The example in Figure 7 is only to show the range of possibilities that exist from a system with capability to detect water surface per pulse and determine depth from timing of the water surface and seafloor to the simplest strategy of averaging water surface points and applying a refraction correction in bulk. Both techniques are used in practice and several other approaches between. Figure 8 captures a real scenario of two systems flown over the JALBTCX reference site. Bathymetry for a single flight line from each system was separated into two surfaces, one from the front half of the circular scan and one from the back half, where front and back are relative to flight direction. The difference image, between the front and back scan surfaces, for one system in the top patch above the blue line has a standard deviation of 0.039m and has no noticeable systematic differences. The difference image from the second system shown below the blue line has a higher standard deviation of 0.072 m and exhibits surface wave patterns translated to the bathymetry.

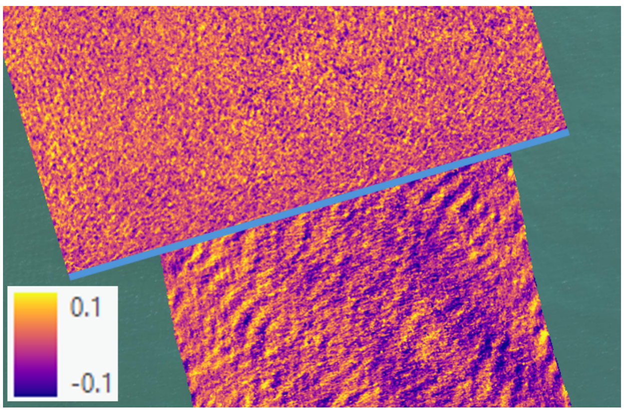

Figure 8. Front and back scan differences from two sensors. Units in meters.

Accurate surface measurements on individual green laser pulses, with or without co-located IR measurement, are still dependent on optical properties, system design, angle of incidence to the surface, environmental conditions, and algorithms which makes it important to understand them and their limitations. One limitation example for a system is provided in Figure 9, where in the clearest waters of Hawaii when no wind is present. Neighbouring pulses may have a clearly detectable surface as shown by the yellow "X" in the waveform on the left or may have no surface return as shown in the waveform on the right. Waveforms are a graph of laser energy detected in the aircraft in units of scaled count versus time in nanoseconds. Processing algorithms typically detect a majority of the water surface when wind is present utilizing IR and green water surface return characteristics and neighbourhood statistics to validate the green and IR surface. Several processing strategies per pulse and receiver are automated to identify pulses that fail to meet required parameters, and a local mean derived surface is applied when necessary. The red points shown in Figure9 come from waveforms that look like the one on the left with the strong surface return. The green points originate from waveforms that look like the one on the right without a strong surface return. In the case of the green points, the "surface" is detected on the half-peak of the volume backscatter below the actual water surface. These biased returns either need to be invalidated or corrected.

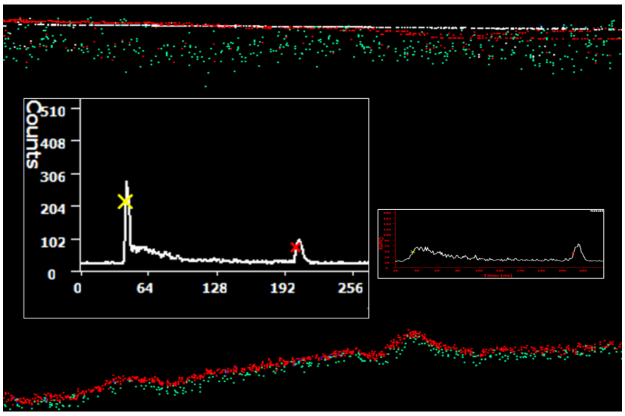

Figure 9. Profile of poor surface-bottom returns in green and detected or modelled surface-bottom returns in red. Waveforms are from pulses taken a few meters from another.

2.3 Signal Processing

Typical signal processing challenges are classifying each pulse as land or water, noise filtering algorithms, and handling sensor specific responses to spurious returns such as sun glint or receiver saturation. Figure 10 shows an area where the manufacturer's provided software misclassified most of the data in less than 1 m of water as class 41-water surface. JALBTCX worked with the manufacturer for access to executables where reclassifying and reprocessing the data would be possible within JALBTCX's editing software. This has allowed the recovery and correction of data as shown on the bottom image. Custom tools like this are common and if not developed with the sensor manufacturer, the data producers develop them by themselves. Use of tools like these must be carefully managed as additional intervention may introduce error, prolong data delivery timelines, and increase cost.

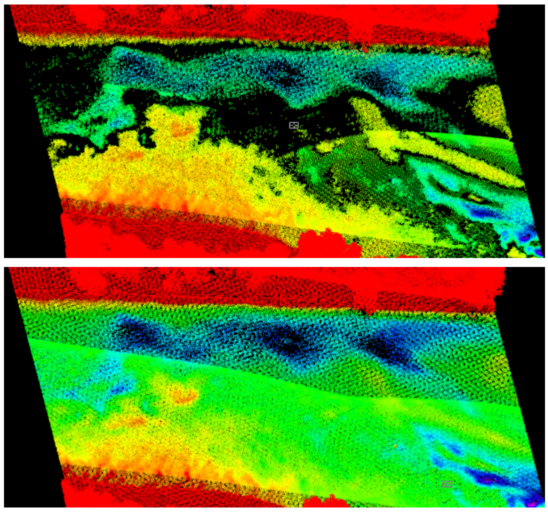

Figure 10. Custom tools used to correct classification and refraction errors from automated processes.

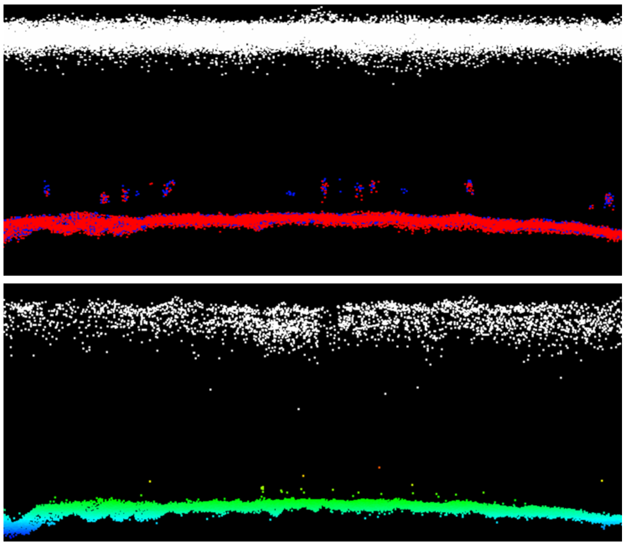

Figure 11. Differences in returns over features between sensors

Feature detection for bathymetric lidar depends on Guenther's complex web and increased point density does not necessarily improve feature detection capabilities alone. The top image of Figure 11 is a profile with 1 m tall features detected in 2018 with two lines, blue, and 2022 with two lines, red, in 5 m of water by one sensor. The bottom profile shows data collected by a different sensor in a single flight with two lines covering the features. Point density of combined lines in the bottom profile is 4 points per square meter, higher than the combined lines of both years of the sensor in the top profile. All points from the delivered data are shown.

Figure 11 demonstrates that bathymetric lidar survey providers must also consider sensor sensitivity, acquisition parameters, and filter settings used in the processing software or post-process editing-classification techniques, so they are optimized to project requirements. Figure 12 is an area collected by two sensors where the missing features in the bottom image were delivered in the noise class. Perhaps the water properties contribute to the difference, but this highlights some of the delivery and expectation difficulties when it comes to traditional lidar means of specifying point density and coverage requirements.

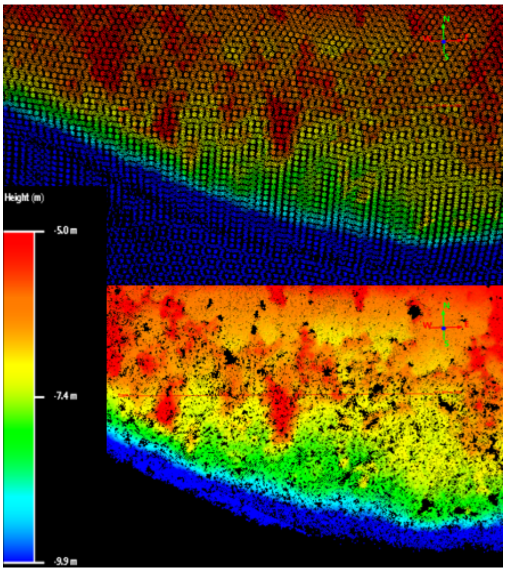

Figure 12. Differences in returns over features between sensors

3. Discussion

The evolution of bathymetric lidar hinges in addressing its inherent challenges through collaboration and innovation. The interplay of propagation-induced biases, water surface detection, and signal processing intricacies forms a new web where foundational principles meet practical realities. These topics serve not just as technical hurdles but as opportunities to enhance the reliability and accuracy of coastal mapping. By situating these challenges within the broader context of community-driven practices and standards, we can work towards solutions that benefit the entire bathymetric lidar ecosystem.

Government agencies, academia, and industry have made significant strides in developing robust methodologies for handling the complexities of bathymetric lidar data. Propagation-induced biases demand careful calibration and an understanding of environmental influences to ensure depth measurements meet international accuracy standards. Similarly, managing water surface uncertainties requires sophisticated models and algorithms, particularly as evolving system designs push the boundaries of what is feasible. Signal processing, encompassing everything from noise filtering to feature detection, emphasizing the need for adaptable tools that address sensor-specific challenges without sacrificing efficiency or precision.

The community also continues work on total propagated uncertainty, a requirement for most hydrographic surveys. Commercial work (Lockhart, 2008) to academia support (Eren, 2019) for NOAA covering the period and advancements on the endeavour with system manufacturers publishing after 2018 with (Ramnath, 2018) and (Brown, 2019). Lockhart using variance in the data, relevant to our practice discussion, to simulated models for subaqueous uncertainties by Oregon State, and a recent manufacturers presentation (Pfenningbauer, 2024) at the JALBTCX workshop factoring in surface statistics and signal information illustrates the progress made. While sensor and analytical modelling are gathering all the pieces, they too rely on internal relative statistics or comparisons to reference datasets for validation. Challenges presented on depth biases highlights that there remains more work to close the gap between theory and practice. The patch test practice from the acoustic survey community for validating systems including the processes necessary for delivery remains necessary in bathymetric lidar. Standard methods and measurement terminology along with sharing of reference data and development of open tools would help align our understanding.

Collaboration is the thread that weaves these solutions together. Efforts like the MAC's centralized resources and the use of reference sites for calibration and validation exemplify how shared knowledge can accelerate progress. These initiatives and the challenges presented highlight gaps in education, standardization, and resource accessibility that must be bridged to achieve broader alignment across the community.

As we address these challenges, it becomes evident that the path forward relies on transparency, openness, and a shared commitment to innovation. Each improvement in methodology or technology strengthens the collective capacity to map and understand our coastal environments more accurately. By continuing to leverage forums for knowledge exchange and advocating for best practices, we lay the groundwork for sustainable advancements in bathymetric lidar.

4. Conclusion

NOAA used the mantra “a rising tide lifts all ships” to encourage the acoustic bathymetry community to support one another for advancement when they were at the government – commercial development crossroads. By embracing collaboration and fostering a culture of shared learning, we can navigate the complexities of this technology with greater confidence and precision. This paper has highlighted critical challenges—propagation-induced biases, water surface uncertainties, and signal processing ~~and~~ emphasized the importance of community-driven solutions to address them.

To ensure the continued growth and effectiveness of bathymetric lidar, we must champion transparency and standardization while remaining open to innovative approaches. The active participation of sensor manufacturers, survey practitioners, and end users is essential to creating a resilient ecosystem that meets diverse application needs.

We encourage all stakeholders to engage with initiatives like the Bathymetric Working Group and similar collaborative efforts. By contributing insights, sharing data, and supporting the development of best practices, we can collectively elevate the standards of bathymetric lidar and ensure its transformative potential is fully realized. Together, we can map clearer waters and achieve stronger depths, fostering trust and reliability in the maps that shape our understanding of the world.

The challenges chosen are to support misunderstandings and questions commonly found today and are from a practitioner's perspective. Responses or corrections are expected and welcomed on the ASPRS BWG discussions page (BWG, 2025).

References

BWG, 2025. Bathymetry Working Group Wiki, American Society for Photogrammetry and Remote Sensing (ASPRS) github.com/ASPRSorg/BWG/wiki, https://community.asprs.org/wg-bathymetry/home (26 May 2025).

Brown, E., Kim, H., Carr, D. et al., 2019. Seahawk lidar. Proc. SPIE 11005, Laser Radar Technology and Applications XXIV, 1100506 (2 May 2019) doi.org/10.1117/12.2519159

Dietrich, J. T., Parrish, C. E., 2025. Development and Analysis of a Global Refractive Index of Water Data Layer for Spaceborne and Airborne Bathymetric Lidar. *Earth and Space Science*, 12. doi.org/10.1029/2024EA004106

Eren, F., Jung, J., Parrish, C., Forfinski-Sarkozi, N, Calder, B., 2019. Total Vertical Uncertainty (TVU) modeling for topo-bathymetric lidar systems, Photogrammetric Engineering & Remote Sensing 85(8), 585-596 doi.org/10.14358/pers.85.8.585

Guenther, G.C., 1985. Airborne Laser Hydrography: System Design and Performance Factors. Rockville, MD: NOAA Professional Paper Series, National Ocean Service 1. geodesy.noaa.gov/library/pdfs/NOAA_PP_NOS_0001.pdf (26 May 2025).

Guenther, G.C., Cunningham, A., Laroque, P.E., Reid, D.J., 2000. Meeting the Accuracy Challenge in Airborne Lidar Bathymetry. Proceedings of EARSel-SIG-workshop Lidar, Dreseden/FRG. https://earsel.org/wp-content/uploads/2016/11/01_1_guenther1.pdf (26 May 2025).

Guenther, G.C., 2007. Airborne Lidar Bathymetry, in: Maune, D.F, (Ed.) 2007 Digital Elevation Model Technologies and Applications: The DEM User Manual. 2nd Edition, Asprs Pubns, Bethesda, MD. https://drive.google.com/file/d/13osSNOwwXAh3aklVOzopn9r_uDVihLWI/view?usp=drive_link (30 May 2025)

Hare, R., 1994. Calibrating Larsen-500 Lidar Bathymetry in Dolphin and Union Strait Using Dense Acoustic Ground-Truth. *The International Hydrographic Review*, *71*(1). https://journals.lib.unb.ca/index.php/ihr/article/view/23220 (27 May 2025)

Lockhart, C., Lockhart D., Martinez, J., 2008. Total Propagated Uncertainty for Hydrographic Lidar to Aid Objective Comparisons to Acoustic Datasets. *The International Hydrographic Review*, 9(2). https://journals.lib.unb.ca/index.php/ihr/article/view/20821/23981 (29 May 2025)

MAC, 2025. Ocean Mapping Community Wiki github.com/oceanmapping/community/wiki, https://mac.unols.org/about/ (26 May 2025).

Philpot, W. (Ed.), 2019, Airborne Laser Hydrography II. https://ecommons.cornell.edu/handle/1813/58722 (28 May 2025)

Pfenningbauer, M., 2024. TPU Estimation – a manufacturer's approach to perform inherent uncertainty control. In: 23rd JALBTCX Airborne Coastal Mapping and Charting Workshop. https://usace.app.box.com/s/04aloz8ex7gnjo41oflzfedqcubwghc3 . https://jalbtcx.usace.army.mil/ . (29 May 2025)

Ramnath, V., Friess, P., Duong, H., Feygels, V., Kopilevich, Y., 2018. Total propagated uncertainty for coastal zone mapping and imaging lidar (CZMIL). *Laser Radar Technology and Applications XXIII* (Vol. 10636, pp. 139-153). SPIE doi.org/10.1117/12.2303893

Schwarz, R.K., Pfeifer, N., Pfennigbauer, M., Mandlburger, G., 2021. Depth Measurement Bias in Pulsed Airborne Laser Hydrography Induced by Chromatic Dispersion, *IEEE Geoscience and Remote Sensing Letters*, vol. 18, no. 8, pp. 1332-1336, Aug. 2021, doi: 10.1109/LGRS.2020.3003088

Wright C.W., Kranenburg, C., Battista, T., Parrish, C., 2016. Depth Calibration and Validation of the Experimental Advanced Airborne Research Lidar, EAARL-B. *Journal of Coastal Research*, 76(sp1):4-17 doi.org/10.2112/SI76-002