# PI-0377 Crewed Aircraft LiDAR Bathymetry in Turbid Water Preliminary Investigation (PI)

*Requested by*

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**July 31, 2025**

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# Executive Summary

## Background

Caltrans frequently conducts underwater terrain mapping, or bathymetry, for safety inspections, such as bridge scouring. Mapping is typically performed using sonar-equipped boats, a method that can be time-consuming and limited in coverage. To improve efficiency, Caltrans is exploring alternatives—particularly airborne LiDAR bathymetry (ALB) using crewed aircraft for mapping the turbid freshwater conditions common at Caltrans sites.

This Preliminary Investigation (PI) provides a comprehensive review of the current state of crewed aircraft-based LiDAR bathymetry technologies with a focus on their suitability for turbid freshwater environments. It evaluates the capabilities and limitations of available ALB systems, including performance in turbid water, technical specifications, operational requirements, and estimated costs. These insights can help assess whether crewed ALB is a practical, cost-effective alternative to traditional methods.

## Summary of Findings

### Turbidity Measurements

LiDAR systems report maximum depth performance based on water turbidity rather than depth, using either the turbidity measurements of Secchi depth or the diffuse attenuation coefficient ($K_d$). Secchi depth provides a simple estimate of water clarity by measuring the depth at which a white disk disappears from a person's view as it is lowered into water, which is subjective and lacks precision. In contrast, $K_d$ offers a more rigorous quantification of how light diminishes with depth due to absorption and scattering, and is often approximated using the formula $K_d \approx 1.7 / SD$. Other turbidity metrics, such as formazine nephelometric unit (FNU), nephelometric turbidity unit (NTU), and formazine turbidity unit (FTU), are commonly used and reported in environmental monitoring but are not suited for evaluating LiDAR performance.

### Commercial ALB Sensors

A variety of ALB sensors are available, primarily from Riegl,[1] Teledyne,[2] and Leica Geosystems.[3] These systems differ in maximum depth—typically ranging from 1 to 3 times the Secchi depth—as well as in other specifications, such as measurement frequency and aircraft platform (helicopter or plane). Newer-generation ALB systems, such as the Riegl VQ-860-G [1], offer improved depth penetration, but we did not find independent studies confirming their performance.

The primary distinction among ALB sensors lies between deep and shallow bathymetric systems. Deep-water sensors typically achieve greater penetration using high-energy, long-duration pulses at low repetition rates [2], which results in lower spatial resolution but allows for deeper mapping. These systems are often large and heavy, requiring deployment from fixed-wing aircraft that may not be ideal for localized or targeted surveys [3].

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[1] Riegl (http://riegl.com/)
[2] Teledyne (https://www.teledyneoptech.com/)
[3] Leica Geosystems (https://leica-geosystems.com/en-us/)

In contrast, shallow-water sensors use lower pulse energy but much higher pulse repetition rates, resulting in higher spatial resolution. This makes them suitable for a broader range of applications, including flood modeling and habitat assessment [2]. High-resolution data have also been shown to improve returns in challenging environments, such as turbulent or vegetated rivers [4].

To increase flexibility, some systems, such as the CZMIL Supernova [5], use dual-channel designs—pairing a high-resolution channel for shallow water with a lower-resolution, high-penetration channel for deeper areas.

<u>Key Insights from Independent Studies</u>

Water turbidity is the most critical factor determining the performance of ALB. Multiple studies show that LiDAR accuracy is generally consistent across commercial ALB sensors and comparable to sonar systems like multibeam echo sounders (MBES) [4], [6], [7]. However, it is reported that when water depth exceeds a LiDAR sensor's specifications, its readings deteriorate significantly, while MBES can continue to measure at greater depths [4]. Although ALB cannot match MBES for deep water, it outperforms MBES in shallow water where boats often face operational challenges [4].

Other environmental factors that degrade ALB performance include:

- Water surface turbulence (whitewater and rapids) [4]
- Water color [6]
- Riverbed composition and coarseness [8]
- Obstructions, such as dense vegetation [2], [4]
- Suspended sediments and debris [2]

Timing surveys to avoid these conditions is crucial for optimal results.

Studies specifically applying ALB to infrastructure tasks, like bridge scour monitoring, are scarce. One notable effort used ground-based bathymetric LiDAR (not ALB) for inspecting underwater infrastructure, demonstrating potential but also highlighting significant limitations in turbid or deeper waters [9].

<u>Alternative and Complementary Sensing</u>

We also explored potential complementary sensing methods. Although we did not find studies that directly use water color or hyperspectral data to calibrate ALB measurements, recent research shows that hyperspectral imaging can estimate turbidity using data-driven techniques [10]. This capability may serve as a valuable supplement to ALB.

## Gaps in Findings

A major gap in the literature is the lack of studies demonstrating the practical use of LiDAR bathymetry for Caltrans applications, especially bridge scour monitoring. Most existing research focuses on surveying or geomorphological analysis rather than cases specific to monitoring underwater infrastructure.

Most studies also rely on airborne LiDAR bathymetry (ALB) systems mounted on planes for large-area scans. There is little research on more focused, high-resolution scanning—such as that needed for detailed bridge inspections—using helicopters. In addition, since many ALB studies focus on surveying marine and coastal regions rather than freshwater environments, we also include several coastal studies even if it might not be as representative of typical Caltrans environments.

Finally, there is a lack of independently published studies on newer commercial LiDAR systems demonstrating their performance, while older models are generally better documented.

## Next Steps

Next steps include contacting commercial manufacturers directly to evaluate whether their sensors are suitable for Caltrans applications. While newer deep-water bathymetric LiDAR systems advertise impressive maximum depths, they often involve tradeoffs, such as lower resolution, that may limit their usefulness for Caltrans' needs. Engaging with manufacturers will also help clarify pricing as cost information is rarely publicly available.

In parallel, it would be valuable to survey turbidity and water depth levels during different times and seasons at Caltrans sites where LiDAR bathymetry is being considered. Given that reported LiDAR maximum depth ratings in the literature generally align with manufacturer specifications, conducting these turbidity assessments will provide a clearer assessment of the feasibility of this system for Caltrans' needs.

# Detailed Findings

## Background

Airborne LiDAR bathymetry uses aircraft-mounted LiDAR sensors to map underwater terrain. ALB systems typically use pulsed green lasers (≈ 532 nm wavelength) that can penetrate water, with depth measured by calculating the round-trip time of laser pulses reflected from the water bottom [11]. Many ALB systems also support topo-bathymetric mapping by combining green lasers with topographic LiDAR operating at infrared wavelengths (typically 1064 nm) [11]. Bathymetric LiDAR has a wide range of applications, including underwater object detection, geomorphology, and risk and disaster management [3], [11].

Traditionally, Caltrans has relied on sonar-based surveying methods, such as MBES mounted on crewed boats or uncrewed surface vessels (USVs), to conduct underwater mapping. MBES systems use sound waves to generate accurate depth measurements but can be time-consuming and limited in coverage [12]. In contrast, ALB can rapidly cover large areas, offering a more efficient alternative to sonar-equipped boats [11]. It also has emerged as a preferred method for capturing river geometry, especially in shallow or fast-flowing environments where MBES is impractical or unsafe [2].

In recent years, there has been growing interest in using uncrewed aerial systems (UAS) equipped with bathymetric LiDAR for Caltrans applications. However, LiDAR sensors designed for UAV platforms are typically less powerful and optimized for shallow, clear water [3], making them poorly suited for the more challenging conditions at many Caltrans sites where water is often turbid or murky. High turbidity significantly reduces LiDAR penetration, limiting its ability to generate reliable underwater models [4].

Given the limitations of both crewed and uncrewed surface vessels, as well as the poor performance of UAS-mounted LiDAR in turbid water, Caltrans is evaluating the use of ALB deployed from larger, crewed aircraft, such as planes or helicopters. These platforms can operate at altitudes of several hundred meters and support more powerful bathymetric LiDAR systems capable of deeper water penetration [3]. While recent commercial ALB technologies show promising capabilities, particularly for deeper and more complex environments, their effectiveness in Caltrans-specific applications—such as bridge scour monitoring—remains uncertain.

This report does the following:

- Reviews published research on the performance of crewed aircraft LiDAR bathymetry in turbid or murky water conditions.
- Compares advantages and limitations of crewed aircraft LiDAR bathymetry relative to existing methods, particularly sonar-based systems.
- Surveys commercially available bathymetric LiDAR systems designed for crewed aircraft with a focus on key specifications and operational requirements.
- Explores complementary sensing methods, particularly the use of hyperspectral imaging to support or enhance LiDAR-based measurements.

# Preliminaries

## Turbidity Measurements

Understanding turbidity measurements and their relationship to maximum depth is important for evaluating the effectiveness of LiDAR bathymetry since depth penetration is highly dependent on water turbidity. In fact, most commercial LiDAR systems report performance not in meters of depth but in terms of turbidity levels, which indicate how effectively the laser can penetrate the water column. However, multiple measurements for turbidity exist in practice, each with distinct advantages and limitations.

### Secchi Disk Measurements

The Secchi disk is a simple tool for measuring water clarity, involving a white disk that is lowered into the water until it is no longer visible. The resulting depth is the Secchi depth, which acts as an indicator of turbidity [11], [13]. LiDAR penetration capability is often expressed as a multiple of Secchi depth, typically ranging from one to three times the measured depth. While the Secchi disk method is simple and widely used, it has several limitations: it is subjective, can be time-consuming, and depends on calm water conditions to yield accurate results [13].

### Diffuse Attenuation Coefficient ($K_d$)

A more scientifically rigorous measurement is the diffuse attenuation coefficient ($K_d$), which quantifies how light diminishes with depth due to absorption and scattering by dissolved substances and suspended particles [13]. $K_d$, measured in $m^{-1}$, can be estimated from Secchi depth using empirical evaluations. One common approximation is given by the formula $K_d \approx 1.7 / SD$ where SD is the Secchi depth [2]. The system performance coefficient $K_dD_{max}$ serves as a key metric in ALB, describing the maximum depth penetration capability of bathymetric LiDAR for a given $K_d$ [13].

According to [2], typical $K_d$ values are classified as:

- Low ($< 0.1\ m^{-1}$) Very clear (open ocean)
- Moderate ($0.1–0.5\ m^{-1}$) Coastal/nearshore waters
- High ($> 0.5\ m^{-1}$) Turbid or sediment-rich water

### Alternative Turbidity Measurements

Beyond the Secchi disk and $K_d$, several other turbidity metrics focus specifically on water clarity and, although not used to measure LiDAR performance, are commonly reported in ALB studies. These include FNU, NTU, and FTU. These units represent equivalent scales of turbidity, but they are based on different detection methods, which can lead to slight variations in results [6].

## Turbidity Ranges in Natural Waters and California Rivers

The Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment provides the following turbidity classifications for typical NTU range values[4]:

- < 0.1 NTU: Water bodies with sparse plant life; drinking water quality
- < 1 NTU: Groundwater
- 1-10 NTU: Water bodies with moderate plant and animal life
- 10-50 NTU: Water with significant planktonic life

[4] https://www.waterboards.ca.gov/water_issues/programs/swamp/docs/cwt/guidance/3150en.pdf

- 20-1000 NTU: Winter storm flows in creeks and rivers

California river quality monitoring data from the United States Geological Survey[5] reports highly variable turbidity levels dependent on both season and location. This wide variability underscores the challenge of implementing LiDAR bathymetry across California's diverse waterway conditions.

## Commercial ALB Sensors

Table 1 lists various ALB sensors, including older models, such as the Riegl VQ-880-G [14], Leica Chiroptera 4X [15], and CZMIL Supernova [5], on which case study evaluations have been published [4], [6], [16], [17], [13]. It also lists newer systems, such as the Riegl VQ-860-G [1] and Leica Chiroptera-5 [18]; although, we did not find any independent studies evaluating their performance.

Although only a few companies manufacture ALB sensors, each offers multiple models with varying specifications, such as laser frequency and maximum depth. Some systems also include infrared LiDAR for topo-bathymetric mapping or additional cameras. Since sensors report maximum depth using different metrics—either SD or the $K_d$—we estimated SD from $K_d$ using the relation: $K_d \approx 1.7 / SD$. Sensor selection depends largely on project size and constraints (which influence aircraft choice), maximum depth, required spatial resolution, and availability [2].

According to manufacturer datasheets, newer-generation sensors generally offer improved maximum depth capabilities. We do not include specific LiDAR resolution metrics as these vary significantly across manufacturers and are difficult to compare directly. Instead, measurement frequency serves as a general proxy for resolution. However, as shown in the table, sensors capable of reaching greater depths typically have lower measurement frequencies, highlighting a tradeoff between resolution and maximum depth, which are noted as two of the most critical factors affecting survey quality in [4].

ALB systems can be broadly categorized between deep and shallow bathymetric sensors. Deep ALB systems prioritize deep-water applications by emitting high-energy pulses at lower frequencies [2]. While this configuration enables greater depth readings, it comes at the cost of spatial resolution. Additionally, these deep ALB sensors tend to be bulky and heavy, typically requiring fixed-wing aircraft to deploy [3]. On the other hand, shallow-water ALB systems typically use low-energy pulses at very high pulse repetition rates. This configuration improves spatial resolution, making these systems well-suited for diverse applications including flood modeling and habitat assessment [2]. To address this tradeoff, some sensors, such as the CZMIL Supernova, use dual-channel designs with separate shallow and deep channels for more flexibility.

[5] https://nrtwq.usgs.gov/ca/constituents/view/63680

**Table 1:** Specifications of Commercial Airborne LiDAR Bathymetry (ALB) Sensors

| | Riegl VQ-880-G [14] | Riegl VQ-860-G [1] | CZMIL SuperNova [5] | Leica Chiroptera 4x [15] | Leica Chiroptera-5 [18] |
|---|---|---|---|---|---|
| **Company** | Riegl | Riegl | Teledyne Optech | Leica Geosystems | Leica Geosystems |
| **Intended Aircraft** | Plane | Helicopter | Plane | Plane | Plane |
| **Year Released** | 2014 | 2024 | 2021 | 2018 | 2022 |
| **Additional Sensors** | RGB | RGB | Hyperspectral | RGBI | RGBI |
| **Typical Sensor Environment** | Topo-Bathy | Bathy | Topo-Bathy | Topo-Bathy | Topo-Bathy |
| **Laser Wavelengths** | Bathymetry (532nm)<br>Topographic (1064nm) | Bathymetry (532nm) | N/S | Bathymetry (515nm)<br>Topographic (1064nm) | Bathymetry (515nm)<br>Topographic (1064nm) |
| **Flying Height** | 600m | 75m–300m | 400m–800m | 400–600 m | 400–600 m |
| **Peak Measurement Frequency** | 550kHz | 100kHz | Shallow: 210kHz<br>Deep: 30kHz | 140kHz | 200 kHz |
| **Maximum Depth** | 1.5 SD | 2.5 SD | Shallow: $2.9/K_d$ (~1.7 SD)<br>Deep: $4.4/K_d$ (~2.6 SD) | $2.7/K_d$ (~1.6 SD) | $3.2/K_d$ (~1.9 SD) |

# Related Research and Resources

## Freshwater Surveys

**Evaluating Methods for Measuring In-River Bathymetry: Remote Sensing Green LIDAR Provides High-Resolution Channel Bed Topography Limited by Water Penetration Capability [4]**

A comprehensive 2024 study evaluated the performance of four commercial airborne LiDAR sensors—Riegl VQ-880-NG, Leica Chiroptera 4X, Teledyne Optech CZMIL Supernova, and Riegl VQ-840-G (helicopter-mounted)—across three Norwegian rivers with varying turbidity (Secchi depths 3 to 9 meters). LiDAR data were compared against traditional bathymetry methods, including GPS transects and MBES. The researchers also assessed factors affecting LiDAR returns, such as water depth, surface roughness, substrate characteristics, water clarity, and vegetation using aerial RGB imagery.

The following conclusions were noted when comparing ALB to MBES:

- MBES can be difficult to operate in shallow, fast-flowing water due to surface operation, and data quality degraded in shallow or sloped riverbeds, whereas ALB data were less noisy in shallow water.
- MBES offers much higher point density—up to 86,000 points/$m^2$ in river pools—while ALB ranged between 7 and 142 points/$m^2$.
- Despite lower point density, ALB showed high accuracy relative to MBES measurements. Deviations, when present, were generally small and attributed mainly to calibration issues.

Key findings include:

- Water clarity is the primary factor limiting LiDAR penetration.
- Data loss was most pronounced in the deepest pools with LiDAR penetration depths closely matching Secchi depths ($\approx$ 3 m, $\approx$ 5 m, > 9 m), confirming Secchi depth as a reliable predictor of sensor performance.
- Signal strength and spatial resolution were the two most important sensor specifications: sensors with higher signal strength but lower point density penetrated deeper (e.g., CZMIL reached $\approx$ 1 m deeper), while higher spatial resolution improved performance in turbulent surface conditions.
- Surface turbulence (whitewater and rapids) and dark riverbed vegetation further reduce LiDAR returns.
- Some sensor-specific biases were noted, such as greater depth deviations for the Riegl VQ-880 in certain rivers and reduced Leica Chiroptera 4X performance in shallow areas.

**Assessment of the Suitability of Green LiDAR in Mapping Lake Bathymetry [6]**

The same group from [4] also studied several clear lakes in Norway in 2023, with turbidity levels from 0.31 to 0.47 FNU and Secchi depths around 6 meters. They evaluated ALB sensors—Riegl VQ-880-GH, Leica Chiroptera 4X, Teledyne Optech CZMIL Supernova, and Riegl VQ-840-G—and compared results to MBES data.

Since the study was conducted in exceptionally clear lakes, the findings may not fully extend to turbid water environments. However, several key insights remain relevant:

- Comparisons between ALB and MBES datasets reveal generally high precision when examining mean and median residuals.

- Residual depth differences between LiDAR sensors were typically centered around zero suggesting no systematic measurement bias.
- ALB point density ranges from approximately 80 points/m² in select shallow lake regions to below 2 points/m² near the maximum depth limit. This finding suggests that reported maximum depths on ALB sensors can be misleading as the resolution at those depths can be significantly limited.

**Remote Sensing of River Bathymetry: Evaluating a Range of Sensors, Platforms, and Algorithms on the Upper Sacramento River, California, USA [16]**

There is limited existing literature on the effectiveness of ALB in California's freshwater environments. However, a 2018 study investigated ALB performance along the Sacramento River, which exhibited turbidity levels around 3 NTU. The researchers used the Riegl VQ-880-G LiDAR system and compared its results with spectral data collected in the field as well as multispectral satellite imagery and hyperspectral data.

The study found that the bathymetric LiDAR system produced the most accurate and precise depth measurements—within a 5% error margin—but only in shallow waters up to 2 meters deep. In deeper areas, the system failed to detect bottom returns, resulting in significant data voids in the LiDAR-derived depth map. Based on these findings, the study concluded that ALB alone is insufficient for comprehensive fluvial remote sensing or river morphology studies. Instead, a hybrid approach that supplements ALB with traditional field surveys in deeper regions beyond the LiDAR's effective range was recommended.

**Field Evaluation of a Compact, Polarizing Topo-Bathymetric LiDAR across a Range of River Conditions [8]**

While this preliminary report focuses on ALB systems mounted on crewed aircraft, we also examine UAV-based LiDAR bathymetry for shallow river mapping. One such study examined three sites along the Colorado River with varying water conditions, including turbidity, chlorophyll concentration, and bed composition.

The study employed a lightweight topo-bathymetric LiDAR system called EDGE, developed by ASTRALiTe for UAV deployment. Designed for flights at approximately 20 meters above the water surface, EDGE™ is rated to penetrate depths exceeding 1.5 times the Secchi depth.

Under optimal conditions—turbidity less than 1 NTU, chlorophyll concentration below 0.8 µg/L, and a sandy riverbed—the LiDAR system successfully detected depths up to 9.3 meters. However, performance declined in more turbid or coarser-bedded conditions. In an area with 12 NTU turbidity, bed returns were only observed up to 1 meter deep. Similarly, in a gravelly section with 6 NTU turbidity, returns were limited to depths of 0.95 meters.

## Coastal Surveys

**Analysis of Depths Derived by Airborne LiDAR and Satellite Imaging to Support Bathymetric Mapping Efforts with Varying Environmental Conditions: Lower Laguna Madre, Gulf of Mexico [7]**

A separate 2017 study conducted an airborne LiDAR survey campaign over Lower Laguna Madre in the Gulf of Mexico using the Chiroptera LiDAR system and compared it to MBES measurements. Although the study focused on a coastal water body, it was conducted in three distinct areas with a wide range of turbidity levels, providing valuable insight into LiDAR performance under varying water conditions.

The main findings revealed a consistent pattern: sonar recorded deeper measurements than LiDAR across all sites. Mean depth differences between LiDAR and sonar increased with higher turbidity, highlighting a key limitation of LiDAR. Overall, only 51% of the lagoon fell within acceptable limits for bathymetric mapping using LiDAR.

**Effect of Turbidity, Temperature and Salinity of Waters on Depth Data from Airborne LiDAR Bathymetry [17]**

Another study conducted in Indonesian coastal waters used the Leica Chiroptera 4X system to measure the effect of different water conditions on LiDAR readings. On average, the study concluded that the LiDAR sensor could penetrate water to depths of approximately 1.5 to 2 times the Secchi depth. In areas with clear water, LiDAR was able to reach depths of up to 7 meters, while in turbid waters, penetration was limited to around 3 meters. The study also observed that variations in water column properties, such as temperature and salinity, can affect LiDAR depth accuracy by approximately 4 to 6 millimeters.

**CZMIL (Coastal Zone Mapping and Imaging Lidar) Bathymetric Performance in Diverse Littoral Zones [13]**

The manufacturers of the CZMIL LiDAR sensor conducted a comprehensive peer-reviewed study evaluating its performance across coastal regions with varying turbidity levels, quantified using the $K_d$. Coastal regions included relatively clear waters in Florida and Hawaii ($K_d < 0.08\ m^{-1}$), moderately clear waters along the east coast of South Korea ($K_d$ between 0.08 and 0.2 $m^{-1}$), turbid waters in Lake Michigan ($K_d$ between 0.2 and 0.4 $m^{-1}$), and highly turbid waters in the Mississippi Gulf ($K_d > 0.4\ m^{-1}$).

In clear waters, CZMIL performed very well with depth measurements reaching up to 65 meters off the Big Island of Hawaii. In moderately clear waters along Korea's eastern coast, the maximum detectable depth was approximately 30 meters, consistent with the system's $K_dD_{max}$ specification. In the turbid waters of Lake Michigan, the study noted that increased turbidity near shore—due to river flow and industrial activity—that could not be mapped by CZMIL. In this area, where $K_d$ exceeded 0.25 $m^{-1}$, CZMIL was able to map depths only up to about 12 meters. Lastly, in the very turbid Mississippi Gulf, CZMIL achieved bathymetric measurements to depths of around 9 meters with $K_d$ values ranging from 0.3 to 0.4 $m^{-1}$.

The authors also noted that CZMIL incorporates a turbid water module (TWM) within its data processing workflow, designed specifically to extract bathymetry data from turbid waters and less reflective, muddy seafloors. This module uses advanced signal processing techniques to detect bottom returns; however, the study did not explain the exact methods employed.

## ALB Operational Requirements

**Airborne LiDAR Bathymetry - Best Practice Manual [2]**

Although not a peer-reviewed study, this handbook—produced by the group that conducted the surveys in [4], [6]—offers valuable insights and practical guidelines for ALB operations, including resources and operational requirements.

In particular, the study emphasizes that successful surveys depend on timing and specific environmental conditions. When mapping rivers and lakes, factors, such as water quality, suspended sediment and debris, turbulence, whitewater, rapids, and aquatic biomass, can absorb or scatter laser energy, reducing the sensor's effectiveness.

## ALB Applications for Infrastructure Monitoring

### Feasibility of Using Green Laser in Monitoring Local Scour around Bridge Pier [19]

Independent studies on the application of bathymetric LiDAR for Caltrans-related purposes are limited. Notably, researchers at Florida Atlantic University have investigated the use of LiDAR for bridge scour analysis. However, these studies did not employ ALB. Instead, they used a ground-based Leica Scan Station II equipped with a green laser (532 nm).

In one such study, the team developed an experimental setup to assess LiDAR's effectiveness for detecting bridge scour in a laboratory environment. A prefabricated scour hole was used, and water turbidity was adjusted using kaolinite powder to achieve levels between 1.2 and 20.8 NTU with water depths ranging from 0.38 to 0.6 meters. Underwater LiDAR scan data were compared to dry scan data of the same scour hole. The results showed that as turbidity increased, detected water depth decreased and absolute error increased—highlighting while LiDAR can feasibly detect scour, its accuracy is constrained by water turbidity.

### Feasibility of Using Green Laser for Underwater Infrastructure Monitoring: Case Studies in South Florida [9]

The study from [19] was extended to real-world case studies, focusing on bridges over rivers in Florida using the Leica Scan Station II.

In one case, a railroad bridge was examined where the average water turbidity was measured at 0.45 NTU and the maximum depth was 2.4 meters. The study reported that the green laser was unable to reach the bottom of the bridge pier due to high water turbidity. For a highway bridge with an average surface turbidity of 1.74 NTU and a maximum depth of 2.7 meters, the green laser was effective for underwater scanning around the bridge. The survey confirmed there was no visible scour around the left end pier. In another highway bridge case, the water was highly turbid with an average turbidity of 5.25 NTU and a depth of 0.28 meters. In this instance, the green laser again failed to reach the bottom due to the high turbidity.

These case studies underscore the significant impact of water turbidity on the effectiveness of green laser-based LiDAR for underwater bridge scanning.

## Hyperspectral Imaging

This review could not find a definitive method for calibrating LiDAR bathymetry using water properties, such as water color or hyperspectral imagery. However, there is extensive research on the use of hyperspectral imagery for estimating water turbidity. This area of study could be valuable for evaluating the effectiveness of Caltrans' surveys as previous research has shown a strong correlation between turbidity and ALB survey quality [4], [16].

**Estimation of Water Depths and Turbidity from Hyperspectral Imagery Using Support Vector Regression [10]**

For example, one study demonstrated an empirical approach for estimating turbidity from hyperspectral imagery. In this study, hyperspectral data were collected with an ITRES Compact Airborne Spectrographic Imager (CASI)-1500 sensor over the Blue and Colorado Rivers. By pairing hyperspectral data with in-situ measurements, a simple classifier was trained to estimate water turbidity. The method achieved a root mean square error (RMSE) of around 1.2 NTU when compared to independent turbidity measurements.

**Water Turbidity Retrieval Based on UAV Hyperspectral Remote Sensing [20]**

This study used UAV-based hyperspectral imaging to develop and validate turbidity retrieval models in aquaculture ponds and irrigation ditches. Among four tested models, the band ratio and partial least squares (PLS) models showed the highest accuracy, supporting its applicability for monitoring water quality in small inland water bodies.

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