Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

PRESERVING UNDERWATER CULTURAL HERITAGE: COMBINING SATELLITE IMAGES WITH A NOVEL FLASH LIDAR PLATFORM

Eleonoor BOSCH(*), Fabien LANGENEGGER(**), Peter GEGE(***), Jean-Christophe ROULET(*), David NGUYEN(*), Jannis HOLZER(*), Daniele CERRA(***), Sonia WUETHRICH(**) & Christophe PACHE(*)

(*)Sensing & Control Group, CSEM SA - Neuchâtel, Switzerland
(**)Neuchâtel's Cantonal Archaeology Office (OARC) - Hauterive, Switzerland
(***)German Aerospace Center, Earth Observation Center, Remote Sensing Technology - Institute Oberpfaffenhofen, Weßling, Deutschland
Corresponding author: fabien.langenegger@ne.ch, eleonoor.bosch@csem.ch

EXTENDED ABSTRACT

Il sito culturale di Les Argilliez, nel lago di Neuchâtel in Svizzera, fa parte del più ampio sito patrimonio mondiale dell'UNESCO "Palafitte preistoriche intorno alle Alpi". Risale alle culture del Cortaillod classico (3841-387 a.C.) e del Cortaillod tardo (circa 3500 a.C.). Misure fotogrammetriche condotte nel 2014 hanno rivelato la presenza di 4.834 palafitte in legno in due zone: una occidentale densamente popolata e una orientale più sparsa, entrambe tra i 2 m e i 3 m di profondità. Nonostante queste aree siano protette, il sito corre due pericoli: i fenomeni di erosione e la proliferazione di specie invasive di cozze, nello specifico la *Dreissena rostriformis bugensis* (cozza quagga) e la *Dreissena polymorpha* (cozza zebra).

L'erosione, causata dalle correnti lacustri e dalle variazioni di profondità, è stata esacerbata dal riscaldamento globale, che abbassa il livello dell'acqua nei laghi e influisce sui modelli dei flussi, costituendo un pericolo per la conservazione del sito per le generazioni future. Inoltre, la proliferazione di cozze invasive potrebbe portare alla perdita di materiale archeologico, in particolare quello organico come il legno. Per valutare e quantificare questi rischi, è essenziale un monitoraggio regolare del sito.

Mappe 3D ad alta risoluzione del sito, se acquisite regolarmente, possono essere combinate con l'analisi spettrale dei dati delle immagini satellitari per fornire informazioni complete sui cambiamenti delle caratteristiche del fondo del lago e delle strutture del sito, nonché sulla proliferazione delle cozze, in modo da poter valutare appieno i pericoli ambientali del sito. Queste tecniche potrebbero rappresentare un'alternativa a quelle attuali, che prevedono l'impiego di sommozzatori per visitare il sito e documentare fotograficamente le variazioni riscontrate. L'analisi automatizzata e regolare dei dati di *point cloud* e delle immagini satellitari potrebbe rilevare tempestivamente fenomeni che potrebbero richiedere interventi.

A causa dell'estensione dell'area, della bassa profondità dell'acqua e della variabilità meteorologica locale, le tecniche di acquisizione di immagini subacquee in 3D, come la fotogrammetria e il sonar, non sono adatte a generare frequentemente le mappe 3D necessarie per monitorare il sito di Les Argilliez. La fotogrammetria é costosa in termini di tempo investito da sommozzatori, processamento dei dati e risorse informatiche, e la qualità delle immagini dipende dalla trasparenza dell'acqua e dalle condizioni meteorologiche. I dati sonar acquisiscono risposte multiple in acque poco profonde, che creano l'effetto *multipath* degradando la qualità dei dati. Pertanto, per la conservazione del sito e il monitoraggio dell'erosione a Les Argilliez, è stata sviluppata una nuova piattaforma di acquisizione immagini 3D basata sulla tecnologia *flash lidar* (*light detection and ranging*), in combinazione con l'analisi spettrale di dati satellitari Sentinel-2.

Il *flash lidar* è ottimizzato per le applicazioni subacquee, e progettato per raccogliere dati di point clouds 3D da un veicolo di superficie senza equipaggio (USV dall'inglese *Unmanned Surface Vehicle*) di medie dimensioni. Il lidar è compatto, alimentato a batteria e dotato di un array sul piano focale di 128×128 pixel. Ciascun pixel è dotato di specifici circuiti elettronici e di tempo di volo (ToF dall'inglese *Time of Flight*) per migliorare l'acquisizione dei dati in acque dalla elevata torbiditá.

La piattaforma è stata progettata per consentire rilevamenti regolari ed efficienti lungo traiettorie predefinite, permettendo un'analisi coerente del sito nel tempo. Le prime campagne sono state effettuate lungo linee di erosione pre-programmate per mappare il profilo del fondo del lago e le sue dinamiche. Un sonar monoraggio è stato utilizzato in parallelo al lidar per validare le misure di profondità ottenute. Infine, una serie di mattoni di terracotta sono stati posizionati sul fondo del lago e usati come riferimento di dimensioni note per valutare le prestazioni del lidar. In questo studio vengono presentati i risultati delle campagne di test preliminari.

Immagini satellitari multispettrali sono state confrontate con gli spettri di riflettanza simulati per sabbia, macrofite e cozze. Nell'articolo vengono riportati esempi di monitoraggio del sito dallo spazio con immagini del satellite Sentinel-2, che identificano anomalie spettrali correlate alla proliferazione delle cozze quagga nell'area, confermate da indagini subacquee. Nuove immagini Sentinel-2 vengono acquisite ogni 5 giorni, permettendo un monitoraggio periodico dell'area per osservare le dinamiche del fenomeno.

I due tipi di acquisizione di dati presentati consentono di identificare, quantificare e tracciare in modo efficiente i rischi ambientali che minacciano i siti archeologici subacquei come Les Argilliez.

IJEGE, Special Issue 1 (2025): 25-33, DOI: 10.4408/IJEGE.2025-01.S-02
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Les Argilliez, part of the UNESCO World Heritage Site "Prehistoric Pile Dwellings around the Alps," is in Lake Neuchâtel (Switzerland) and dates to the Classical Cortaillod (3841-3817 BC) and Late Cortaillod (around 3500 BC) cultures. Among other artifacts, it consists of 4,834 wooden piles found over a 7000 m^2 area ranging from 2 m to 3 m depth below the water surface. Two dangers threaten the preservation of the site: erosion and the proliferation of invasive mussel species: *Dreissena rostriformis bugensis* (quagga mussel) and *Dreissena polymorpha* (zebra mussel), which pose the specific threat risk of degrading the wooden piles.

This study presents two methods developed for the monitoring of the erosion and mussel populations at Les Argilliez: a new flash lidar based 3D imaging platform and satellite image data analysis. Together, the two data collection schemes allow for efficient identification, quantification and tracking of environmental risks threatening underwater archeological sites, such as this one.

The flash lidar is optimized for underwater applications and designed to collect 3D point cloud data from a medium-sized unmanned surface vehicle (USV). The lidar system is battery-powered and features a 128×128 pixel focal plane array for high resolution point cloud capture. When mounted to the USV, the lidar enables regular and efficient lake surveys, allowing consistent comparison of the same locations over time. The point cloud data enables measuring the height and orientation of the wooden piles and the lakebed profile. The first demonstrative lidar measurement results are presented in this study.

In addition, spectral data from satellite images taken by Sentinel-2 was compared with simulated reflectance spectra for sand, macrophytes and mussels. The processed satellite data successfully identifies spectral anomalies correlated to the proliferation of quagga mussels in the area over a period of four years, and is confirmed by underwater surveys done by divers.

Keywords: *underwater survey, archaeology, erosion, lidar, USV, 3D imaging, remote sensing, quagga mussels, sentinel-2.*

INTRODUCTION

The Les Argilliez cultural heritage site is located in Lake Neuchâtel, Switzerland (Fig. 1) and is part of the larger UNESCO World Heritage Site "Prehistoric Pile Dwellings around the Alps." It dates to the Classical Cortaillod (3841-3817 BC) and Late Cortaillod (around 3500 BC) cultures. A photogrammetric survey conducted in 2014 revealed the presence of 4,834 wooden piles over 7000 m^2, some examples are shown in Fig. 2. The area is divided into two zones: a densely packed western zone where the piles are barely visible, often fully or partially covered by the accumulation of pebbles, and a more scattered eastern zone in which several piles are exposed up to 50 cm above the lakebed (Wüthrich, 2019). The site ranges from 2 m to 3 m depth below the water surface and, despite being protected, two dangers are threatening it: erosion and the proliferation of invasive mussel species: *Dreissena rostriformis bugensis* (quagga mussel) and *Dreissena polymorpha* (zebra mussel).

Fig. 1 - Aerial view of the Les Argilliez cultural heritage site on the North shore of Lake Neuchâtel, Switzerland, with map indicating the site location (insert)

To both the east and west of the site, an erosion front is active, progressively cutting into the protected area. The erosion results from the significant difference in depth between the centre of the site and the periphery, allowing the lake currents to progressively diminish the sediment deposits around the site. While less active than those observed in other parts of the lake, this erosion front must be constantly monitored as currents in the lake change in intensity from year to year and because of the danger to Les Argilliez. Additionally, the preservation of sediment layers is essential because they are rich in scientific information. Observation and analysis of organic matter at Les Argilliez have allowed researchers to trace the evolution of the environment and vegetation since the last ice age. Ancient marshes and thousand-year-old forests, preserved underwater, bear witness to changes in the landscape and the evolution of lake levels over millennia.

The second danger to Les Argilliez is the proliferation of the invasive quagga mussel (*Dreissena rostriformis*) which disrupts ecosystems and poses a significant concern for archaeologists. By covering submerged sites, these mussels make it harder to monitor prehistoric villages, an important task for archaeological services, and present a threat to future generations opportunities for access and engagement with them. The primary concern is the potential alteration of organic remains, including both the sediment layers and the piles, by the mussels. Since their arrival in Lake Neuchâtel, there has not been enough time to assess any possible deterioration

Fig. 2 - Submerged wooden piles in the eastern zone of Les Argilliez

of these crucial archaeological and environmental records.

Two approaches were developed for monitoring the threats to Les Argilliez. The mussel populations are tracked using data processing methods for remote sensing data – namely satellite images from Sentinel-2. In addition, the erosion front and mussel populations are being imaged using a novel flash lidar platform which was developed to regularly collect in-situ 3D point-cloud data from the site. Regular surveys of the erosion front, and periodic monitoring of the mussel populations are essential to understand the evolution of the threats and, if necessary, to take measures for the physical preservation of this World Heritage Site.

For analyzing organic matter content near the shore, satellite images taken by Sentinel-2 are publicly available, and can be processed with spectral analysis techniques which reveal the critical areas of population growth (Cerra, 2024). This technique was tested for the Les Argilliez site to determine whether the mussel populations could be tracked through periodic analysis of satellite images. The collected data will be combined with the results of the 3D survey for continuous assessment of mussel growth.

Several underwater cultural heritage sites use 3D imaging to monitor and assess the state of the site or to track the changes over time. For example, off the coast of Naples, IT, researchers have mapped a cultural heritage site using photogrammetry and sonar, which enabled biologists to manually indicate which 3D surfaces had some organism growth based on the images taken (Bruno, 2019). At this site, water clarity and sunlight conditions, as well as the site depth, made it possible to use cameras and sonar for data collection.

In the Baltic Sea, a group of researchers tested a structured light scanner mounted to a remotely operated vehicle (ROV) which performed a 1.5×10 m survey enabling small object reconstruction with 0.8 mm to 1 mm resolution (Bräuer-Burchardt, 2023). This system does not work in shallow water, given the size of the ROV alone, but provides excellent resolution for 3D reconstruction.

For generating the 3D point cloud data needed in this monitoring effort, conventional underwater 3D imaging techniques, such as photogrammetry and sonar were not suitable. Photogrammetry can be costly in terms of diver's time as well as computing resources, especially when considering a 7000 m^2 area. Further, imaging quality is dependent on water transparency and weather conditions and is highly susceptible to sunlight refraction (Calantropio, 2024). Sonar imaging, another survey method, suffers from multiple reflections in shallow water, causing multipath and degrading the quality of the data (Hansen, 2011). For this, and many other cultural heritage sites, the water depth precludes the use of sonar systems beyond single beam sonars, which may be used to corroborate other depth measurements.

Underwater lidar systems are a promising solution for generating 3D maps efficiently. Active illumination reduces the dependence on weather conditions, and no multipath is generated. Flash lidar may employ a 2D single photon avalanche detector (SPAD) array, such as the one integrated in this research, to collect point cloud images at high resolution and framerate. This combination enables efficient data collection over large areas in all but high-wind weather conditions, further enabling repeat measurements at low incremental cost.

This study presents an overview of the system deployed for collecting 3D point cloud data and reviews in detail the data and methods used in both the lidar survey and the satellite spectral analysis for continuous monitoring. Finally, results of initial campaigns are presented and discussed followed by a conclusion summarizing the implications of the research and areas for future work.

LIDAR PLATFORM DESCRIPTION

The regular survey of Les Argilliez is conducted using the novel flash lidar platform developed for this research. It consists of a battery-powered unmanned surface vehicle (USV) shown in Fig. 3 equipped with navigation sensors, the lidar, and a single beam sonar. Its dimensions are about 128 cm × 80 cm × 60 cm, and the weight is 28 kg (without the lidar). It can either be manually remotely controlled or programmed to follow pre-defined trajectories using an inertial measurement unit (IMU) coupled with a global navigation satellite system (GNSS RTK). The computer on the USV runs software to control the connected equipment:

1. USV: BathyDrone (https://www.bathydrone-usv.com/)
2. USV autonomous control software: QGroundControl (https://qgroundcontrol.com)
3. GNSS RTK: Proprietary firmware, data transferred through RS232 or USB-C connection.
4. Single beam echo-sounder: Hydromagic (Eye4software)
5. Lidar: CSEM proprietary software

QGroundControl is an open-source solution for PX4 or ArduPilot powered vehicles, offering comprehensive setup and control. It supports full configuration of ArduPilot and PX4

Pro, facilitates MAVLink protocol operations, and includes mission planning for autonomous missions. During initial testing, lidar data georeferencing was done using an initial synchronization of the onboard system, with independent time-logging for subsequent data points.

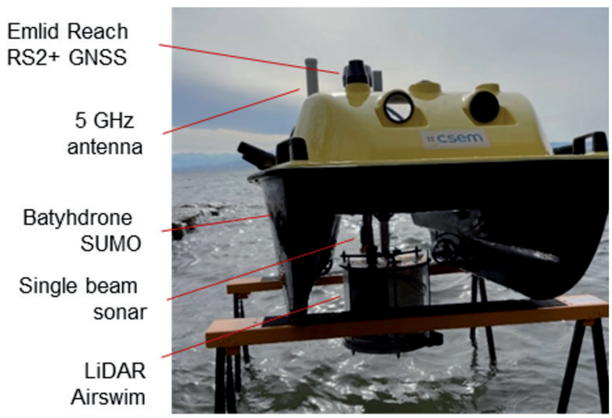

Fig. 3 - USV platform including lidar enclosed in watertight housing (field of view facing down)

The advantages of using a USV include minimal environmental impact due to the absence of a thermic motor, the ability to conduct repeated missions for imaging of the same locations, and a shallow draft of less than 40 cm, which enables operations in shallow water.

The flash lidar (first presented in Pache, 2021) is mounted below the USV, pointing directly down at the lake floor. The lidar alone is 20×17×19 cm and when encased in waterproof housing, it is 23 cm in diameter and 25 cm tall. It is battery-powered from the USV with average power consumption below 27 W.

The lidar integrates a SPAD detector used developed by the Fondazione Bruno Kessler (Italy), originally for space applications (Perenzoni, 2017). By tiling four detectors in a 2×2 array, the system has a total resolution of 128×128 pixels. Each pixel is equipped with integrated direct time-of-flight (ToF) measurement capability and additional logic for operation in turbid water.

The lidar has an adjustable field of view (FoV), focus, and laser power for on-site system optimization, depending on water conditions. For survey at Les Argilliez, a bandpass filter selected to minimize background noise during daytime testing limited the FoV to 35° to avoid vignetting of the laser power from the wavelength shift through the filter.

DATA AND METHODS

To evaluate the changes along the erosion front, four measurement lines perpendicular to the front were defined (Fig. 4). The USV trajectory was programmed to follow these lines while the lidar collects point cloud data. Pile length from the lakebed, for those which can be identified, is measured using the 3D point cloud data. The measurable length of wood piles can be compared between test campaigns to assess changes in pile burial depth which may be due to the movement of sediment.

The point cloud data along each line is also averaged laterally over the FoV of the lidar, to get an average depth measurement from the data collected along the defined trajectory. This creates one 2D profile of lake depth vs. USV position for each erosion line. The lakebed profiles allow for monitoring the evolution of the erosion over time.

Terra cotta bricks with known dimensions were placed directly on the lakebed along erosion line B from Fig. 4. These targets are uniquely identifiable due to white plastic markers attached to each. The bricks can be used to assess the mussel invasion rate, as their material makes them an ideal substrate for mussel attachment, and their well-defined geometry allows for precise evaluation of mussel development. The 3D point clouds of the bricks and wood piles from the lidar, compared over time, can provide information on the mussel population growth. During initial measurements, the bricks also served as reference objects to evaluate the lidar depth- and spatial resolution performance.

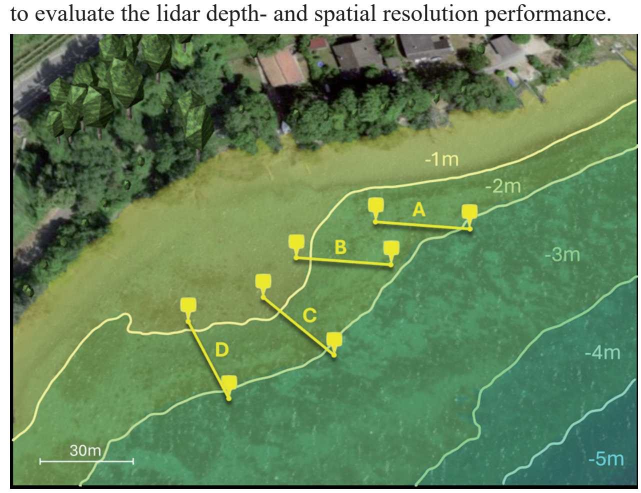

Fig. 4 - Aerial view of the Les Argilliez site with water depth indicated. Four erosion lines, which were selected for depth profile monitoring, are pictured (labelled A-D)

Typical spectra of mussels and other materials both organic and inorganic contributing to the spectral information detected from space are analyzed to assess the feasibility of using satellite images to track mussel populations at Les Argilliez and at which depths it could succeed.

Spectra of mixtures of mussels, typical sand samples and macrophytes have been simulated for a depth of 2.5 m, considering that the site is found at an average depth between 2 m and 3 m, using the WASI software (Gege, 2014), and are reported in Fig. 5. The spectral mixtures have been resampled in the bottom row to the relevant bands of the Sentinel-2 multispectral satellite, in order to assess the impact of these three components to the measured water spectra. Mussels

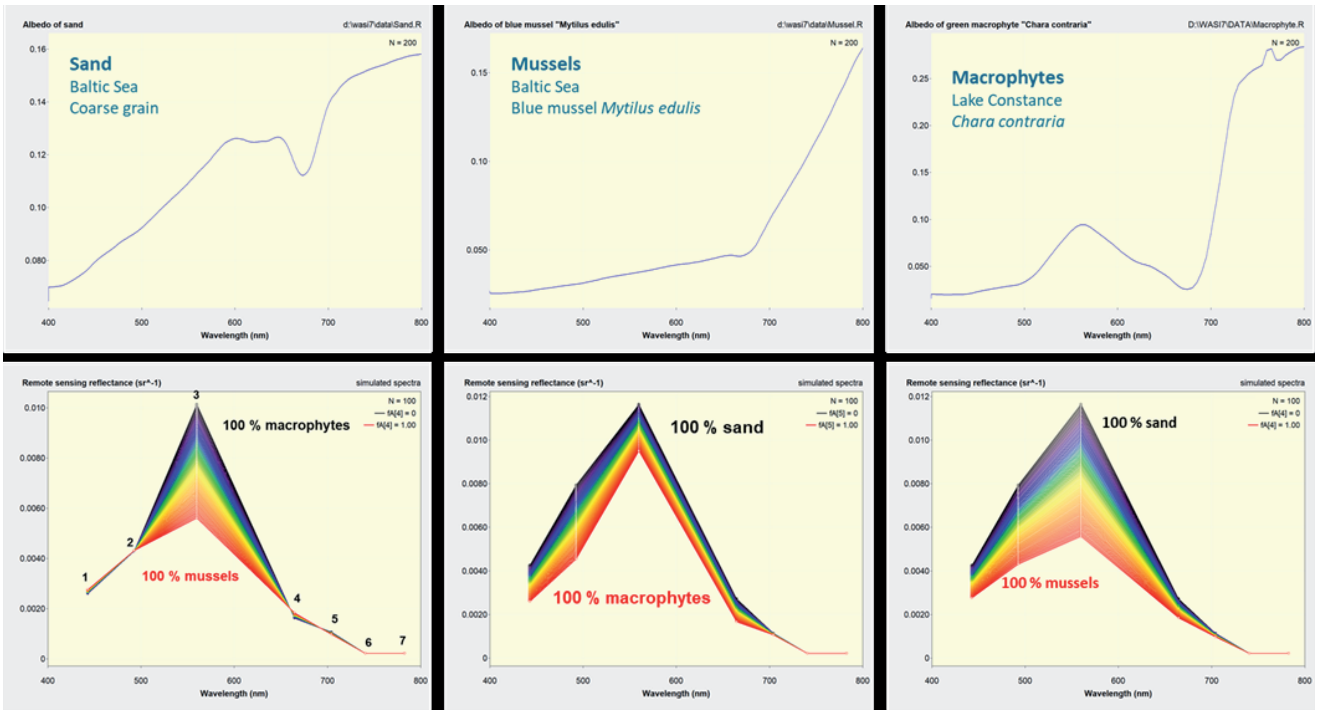

Fig. 5 - *Simulations of the impact of mussels and macrophytes on reflectance spectra at a water depth of 2.5 m. Top: spectra used in the simulation for sand, mussels, and macrophytes. Bottom: separability of each pair of spectra for relevant spectral bands in Sentinel 2. Band 3 in the green range shows significant discrimination between mussels and macrophytes, and bands 1, 2 and 4 provide additional information about the ratio of mussels and sand or macrophytes and sand in an image pixel*

appear to be separable from both sand and macrophytes at the bottom of such shallow inland waters, in the green range from 500 to 600 nm, corresponding to band 3 in Sentinel-2 data.

Satellite images acquired by Sentinel-2 in the proximities of the site and the derived estimated anomaly in the green band are reported in the next section. Therein, anomalies Ag in this range of the spectrum have been computed as:

$$A_g = \frac{G_1 - G_2}{G_1 + G_2} > 0.2 \qquad (1)$$

where G_1 and G_2 are the median reflectance in the green band for images acquired over the month of April in 2018 and 2022, respectively. Here, a normalized difference yields a more robust result, and the threshold of 0.2 has been adjusted manually.

Finally, the map obtained from satellite image analysis was correlated with direct observation by scuba divers from OARC in autumn 2024.

RESULTS AND DISCUSSION

An example of a reconstructed scene along erosion line B in Les Argilliez is shown in Fig. 6 (orange image). This result can be compared to an airborne image captured with a standard camera mounted on a small drone (green image). The area captured by the lidar over the USV trajectory is delineated by the white lines overlayed on the image. The lidar image is color-coded relative to the depth measured by each pixel, with lighter shades indicating the measurement is shorter (target closer to the surface).

The 3D map enables measurement in all three dimensions of the lakebed features, which is especially important in the evaluation of the erosion profile as discussed in the previous section.

In Fig. 7a, the image was captured with a standard camera and the pile (circled in red) is barely visible due to its color blending with the surroundings. In the lidar image of the same pile, (Fig. 7b), it is distinctly visible, with additional details of its tip visible as well as the ability to determine its height from the lakebed.

By comparing the lidar image with one taken underwater by a scuba diver (Fig. 7c), the lateral and depth accuracy and precision of lidar measurements can be assessed. Based on the image distance scale shown on the right side of Fig. 7b, the brick thickness is estimated by the lidar to be 14.6 cm, in very good agreement with the nominal brick thickness of 14 cm. Similarly, the wood pile, whose height from the lakebed is estimated from the point cloud data to be 35 cm. From the camera image, the pile appears 2.5 times taller than the brick height, indicating that the two imaging methods agree.

The repeatability of the lidar measurements is weather- and water condition dependent. Waves and wind can cause motion blur during image capture, and algae growth and lake currents can

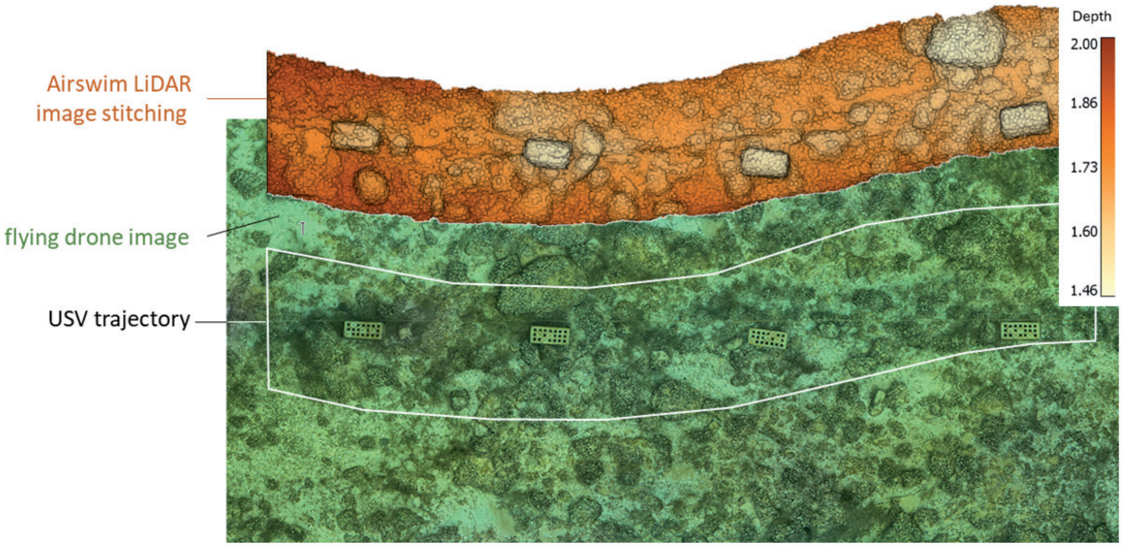

Fig. 6 - Comparison between lidar acquisition (orange) and a standard image taken with a camera from an aerial drone (green)

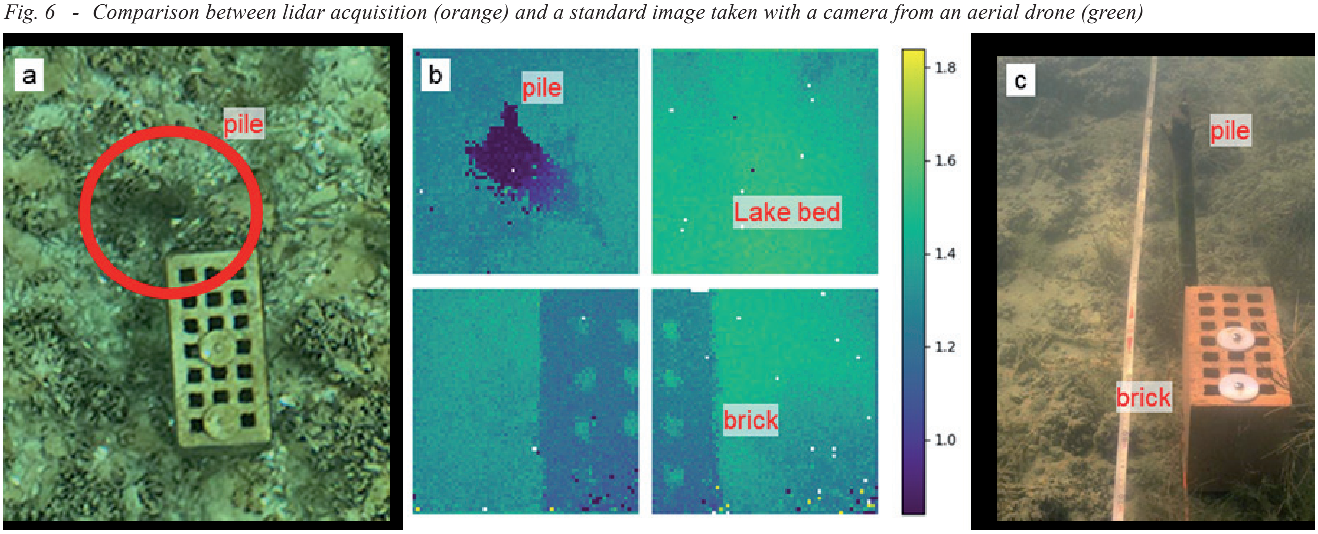

Fig. 7 - a) Image from the water surface (normal camera) of a wooden pile and a test target in Les Argilliez. b) Lidar depthmap at the same location. c) Side-view of the same test target and pile (normal camera). The test target is a terracotta brick measuring 25×12×14 cm and the white alveoli markers are 2×2 cm

cause increased turbidity, reducing lidar image quality. The USV trajectory is dependent on weather conditions as well, as the motor controller must adapt in real time to maintain its heading and speed.

Initial lidar measurements in Les Argilliez started at the end of 2024. Consequently, it is too early to determine the presence and intensity of erosion. The initial erosion front profile data from one of the measurement lines is shown in Fig. 8. The lidar-measured profile (in blue) represents the average depth measured over the lateral FoV (approximately 1.6×1.6 m for a depth of 3 m).

This averaging may account for discrepancies with the single beam sonar profile (in orange), particularly at greater depths where a difference of about 20 cm is observed.

Planned improvements to the lidar data capture platform, including better synchronization across sensors, are expected to improve the lidar measurement performance against the sonar benchmark.

Fig. 9 presents a 3D image of a pile (found in erosion line B from Fig. 4), demonstrating how the distance from the pile end to the lakebed from the lidar point cloud can be used to measure erosion or sedimentation.

In shallow waters near Concise, approximately 5 km south of the heritage site of Les Argilliez, researchers at OARC have documented mussel population spreading. Fig. 11a and Fig. 11b show renderings of satellite images acquired in April 2018 and 2022, respectively, with Fig. 11c showing the 2022 image with overlaid changes from 2018 to 2022 derived from equation (1). The largest change

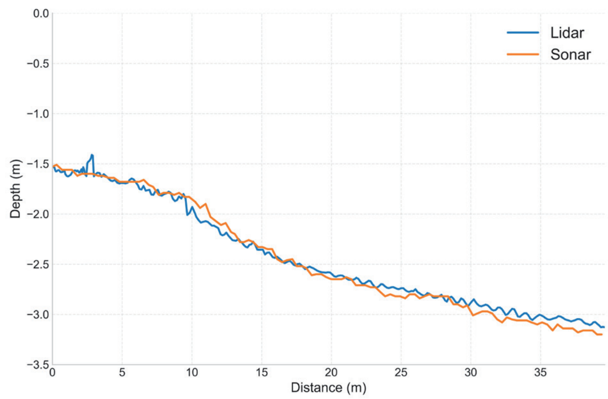

Fig. 8 - Lakebed profile measurement in Les Argilliez (erosion line C). The blue line is the lidar measured depth, and the orange is sonar measured depth

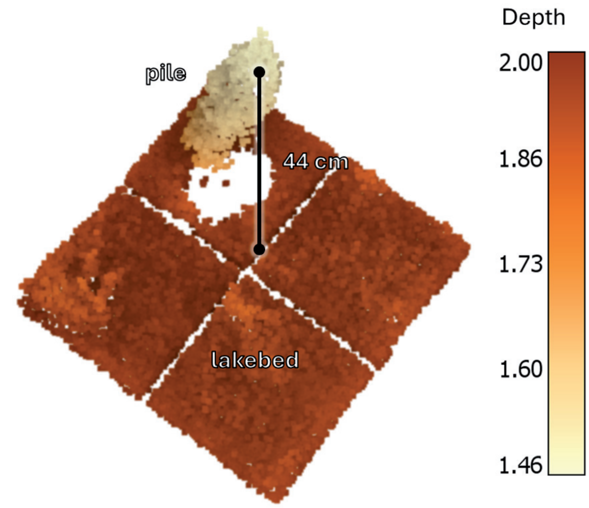

Fig. 9 - Pile to lakebed height measurement (black line)

is depicted in red, confirming the extent of the phenomenon and providing a first identification of critical mussel proliferation areas.

Moving further towards the submerged cultural heritage site, a similar decrease in green reflectance was observed over Saint-Aubin, only 2 km south of Les Argilliez and partially covering the heritage site (Fig. 11d, 11e and 11f). This has been validated on-site with underwater surveys (Langenegger, 2024) which found quagga mussels in several sites, including both Concise and Saint-Aubin. In the Bay of Concise intensified colonization is reported, with areas exploited for gravel showing mussels on the pebbles, confirming observations from satellite images. A photographic survey in 2022 found a clear increase in colonization of quagga mussels in Saint Aubin compared to 2019, confirmed by the changes detected from satellite data in Fig. 11d and Fig. 11e, which are highlighted in Fig. 11f.

Finally, aerial images taken with a drone in 2022 have significant dark areas compared with those of 2018 which correspond to the parts colonized by mussels (Fig. 10).

CONCLUSION

The flash lidar technology developed by CSEM and the spectral analysis developed at OARC demonstrate significant potential for monitoring underwater archeological sites. They can be effectively used to monitor erosion and invasive species populations as well as site degradation.

The compact size, light weight, and low power consumption of the lidar make it ideal for integration on medium-sized Unmanned Surface Vehicles (USVs), facilitating regular and cost-effective surveys of critical sites. Additionally, the lateral and measurement distance accuracy and resolution are well-suited for rapid and precise cartography of large areas, which can later be refined using more precise but costly techniques such as photogrammetry.

Open source and inexpensive satellite data can be used to gather information on phenomena like the spread of invasive quagga mussels on the lake bottom. Despite promising results,

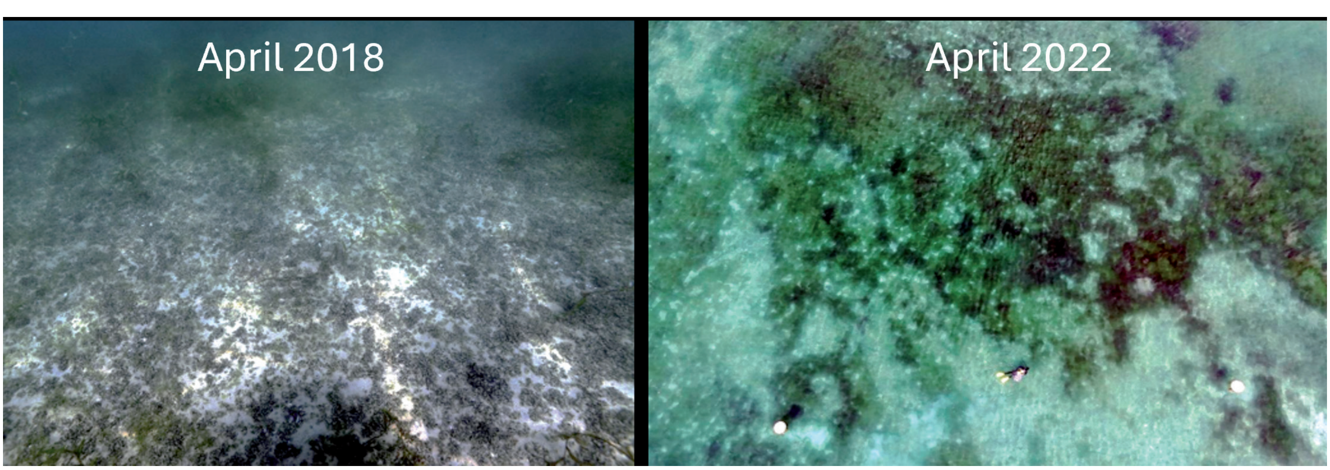

Fig. 10 - Increase in mussel density at the Saint-Aubin (lake Neuchâtel) as seen in camera images taken from a drone

challenges in spectral separability persist, particularly in deeper waters where detection becomes more difficult. This necessitates further studies. Moreover, ongoing research should aim to better understand the implications of invasive species proliferation for the preservation of underwater archaeological structures in sites affected by this phenomenon.

The remote sensing modalities and examples of deployment presented in this paper demonstrate advances toward comprehensive underwater archeological site monitoring and risk quantification. They will be used for regular site monitoring, such that changes can be identified and tracked to inform preservation measures needed to protect Les Argilliez.

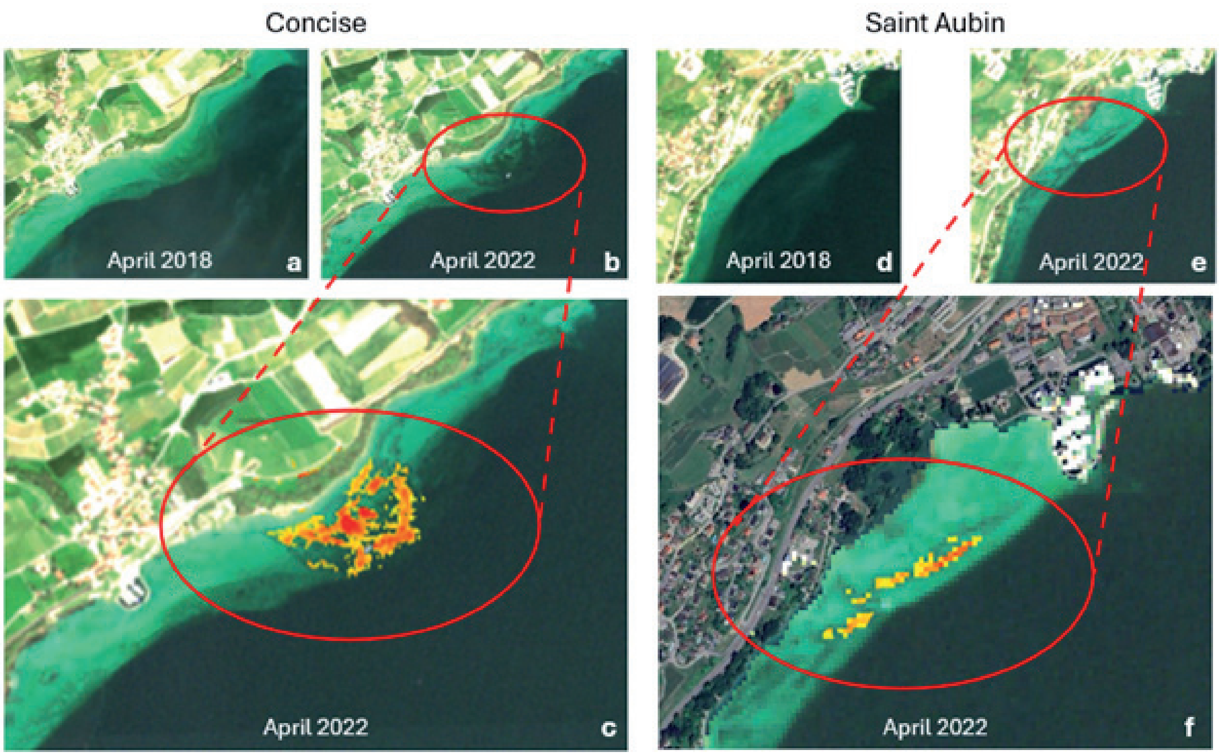

Fig. 11 - (above) Sentinel-2 image composites acquired over Concise (NE) for the months of April 2018 (a) and April 2022 (b) and Saint-Aubin (NE) for April 2018 (d) and 2022 (e). (below) Anomalies detected in the evolution of reflectance in the green portion of the spectrum near Concise between 2018 and 2022 (c) and Saint-Aubin between 2018 and 2022 (f), suggesting colonization of quagga mussels in these areas. Values gradually changing from yellow to red indicate a relative drop in green reflectance from 33% to 60% or more, respectively

REFERENCES

Bräuer-Burchardt C., Munkelt C., Bleier M., Heinze M., Gebhart I., Kühmstedt P. & Notni G. (2023) - *Underwater 3d scanning system for cultural heritage documentation*. Remote Sensing, **15**(7): 1864. https://doi.org/10.3390/rs15071864ü

Bruno F., Lagudi A., Collina M., Medaglia S., Davidde Petriaggi B., Petriaggi R., Ricci S. & Sacco Perasso C. (2019) - Documentation and monitoring of underwater archaeological sites using 3D imaging techniques: The case study of the "Nymphaeum of Punta Epitaffio" (Baiae, Naples). I*nternational Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **XLII**-2/W10: 53-59. https://doi.org/10.5194/isprs-archives-XLII-2-W10-53-2019

Calantropio A. & Chiabrando F. (2024) - Underwater Cultural Heritage Documentation Using Photogrammetry. *Journal of Marine Science and Engineering*, **12**(3): 413. https://doi.org/10.3390/jmse12030413

Cerra D., Gege P., Plattner S., Langenegger F., Wüthrich S., Roulet J.-C. & Droz F. (2024) - *Assessing the spread of invasive mussels in lake Neuchâtel as a potential threat to the Les Argilliez heritage site with Sentinel-2.* IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium, Athens, Greece, 2024: 3376-3379. Doi: 10.1109/IGARSS53475.2024.10640529

Gege P. (2014) - *WASI-2D: A software tool for regionally optimized analysis of imaging spectrometer data from deep and shallow waters.* Computers & Geosciences, **62**: 208-215.

Hansen R. E., Callow H. J., Sabo T. O., Synnes S. A. V. (2011) - Challenges in seafloor imaging and mapping with synthetic aperture sonar. *IEEE Transac-*

tions on Geoscience and Remote Sensing, **49**(10): 3677-3687. https://doi.org/10.1109/TGRS.2011.2155071

Langenegger F. (2024) - *Estimating the spread of invasive Quagga mussels on the lakebed of lake Neuchatel as a potential threat to the Les Argilliez.* OARC internal report, 2024.

Pache C., Meier C., Droz S., Nguyen D., Roulet J.-C., Pollini A., Hauge T. F. & Droz F. (2021) - *Miniature Flash lidar for Bathymetry: An Experimental Proof-of-Concept.* 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, Brussels, Belgium, 2021: 8531-8533. Doi: 10.1109/IGARSS47720.2021.9554034

Perenzoni M., Perenzoni D. & Stoppa D. (2017) - *A 64×64-Pixels Digital Silicon Photomultiplier Direct TOF Sensor With 100-MPhotons/s/pixel Background Rejection and Imaging/Altimeter Mode With 0.14% Precision Up To 6 km for Spacecraft Navigation and Landing.* IEEE Journal of Solid-State Circuits, vol. **52** (1): 151-160, Jan. 2017. Doi: 10.1109/JSSC.2016.2623635

Wüthrich S. (2019) - *Gorgier - Les Argilliez.* Dictionnaire historique de la Suisse (DHS). https://hls-dhs-dss.ch/fr/articles/058004/2019-04-03/

Received February 2025 - Accepted July 2025