Indonesia: Insights into a field campaign aiming to map the underwater environment of Pramuka Island using an underwater laser scanner, a multibeam echosounder and an airborne bathymetric lidar

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SUMMARY

Unlike traditional echosounders, which transmit acoustic waves, the underwater laser scanner ULi employs optical radiation to perform high-resolution bathymetric and structural mapping in clear water environments. To assess the achievable measurement capabilities as well as the performance of the sensor relative to established acoustic techniques, a field campaign in the clear coastal waters around Pramuka Island, Indonesia, was carried out.

To enable a direct comparison between optical and acoustic sensing approaches, the underwater laser scanner was simultaneously operated with a conventional multibeam echosounder (MBES). To additionally map the water-land transition zone of the island, the airborne bathymetric laser scanner (ABS) was used.

It can be concluded that (1) the airborne bathymetric laser scanner ABS and the underwater laser scanner ULi provide a higher spatial detail and surface fidelity compared to the MBES. This (2) particularly applies to shallow areas (< 10 m depth) where optical propagation remains effective.

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1. MOTIVATION AND INTRODUCTION

Driven by the enormous potential that laser scanning systems already deliver on the landside, the interest in capturing respective 3D data also in aquatic environments, continuously increases [Hildebrandt et al., 2008]. Hereby, laser scanners are of particular interest in the scope of underwater infrastructure elements including port facilities, offshore wind turbines, pipelines, submarine cables and drilling platforms, which all require regular inspection, maintenance and repair operations [Nauert & Kampmann, 2023]. Driven by the potential to operate terrestrial laser scanners on water-based platforms such as vessels or unmanned vehicles, the development of underwater laser scanners was strongly driven forward in the past years. One example for a recently developed system is the underwater light detection and ranging system ULi, which was developed by the Fraunhofer IPM in Germany and purchased by the HafenCity University Hamburg.

Since the quality of the achievable results delivered from the underwater laser scanner highly depends on the quality of the water, the first static test measurements were carried out in laboratory environments offering clear water conditions. Within this environment, ULi was able to fully resolve a Böhler-Star test object in low turbid water (0.9 NTU) at a distance of 18 m, in moderate turbid water (2.4 NTU) at 5 m measurement range and in turbid water (4.6 NTU) at a maximum scanning range of 1.4 m [Heffner et. al, 2025]. Following, a dynamic approach in a real-world scenario was conducted. For this purpose, the underwater laser scanner was mounted onto the HCU survey vessel DVocean and deployed in a side-channel of the river Elbe. Within this channel, a turbidity level of 6 NTU was measured, which did not allow to retrieve any reflection from the transmitted laser. To assess what the sensor is generally capable of under real-world conditions, further tests under clearer water conditions were sought. As a result of these efforts, a collaborative scientific project between the HafenCity University Hamburg and the Indonesian Institute Teknologi Bandung on Pramuka Island, Indonesia, was carried out.

Within this project, the primary goal was to create an open-source and free-of-charge 3D data model of the shoreline of the Indonesian island Pramuka. In order to do so, conventional acoustic instruments as well as advanced optical instruments, including the underwater laser scanner ULi and the airborne bathymetric laser scanner ABS, were used. Hence, the project did not only offer the opportunity to conduct further tests of the underwater laser scanner within the clear coastal waters of Pramuka Island, but also to compare the results derived from the different sensor techniques.

2. TEST ENVIRONMENT

The Thousand Islands Archipelago is an area north of the indonesian capital city Jakarta and located between longitude 106 ° 25’ – 106 ° 40’ and latitude 02 ° 24’ – 05 ° 45’ within the Java Sea. The archipelago, shown in Figure 1 (a), consists of many small islands for which the administrative hub is the 16 ha large island Pramuka. Pramuka is situated roughly 50 km north of Jakarta and can be reached by ferry within 1 to 3 hours from the harbour Marine Ancol.

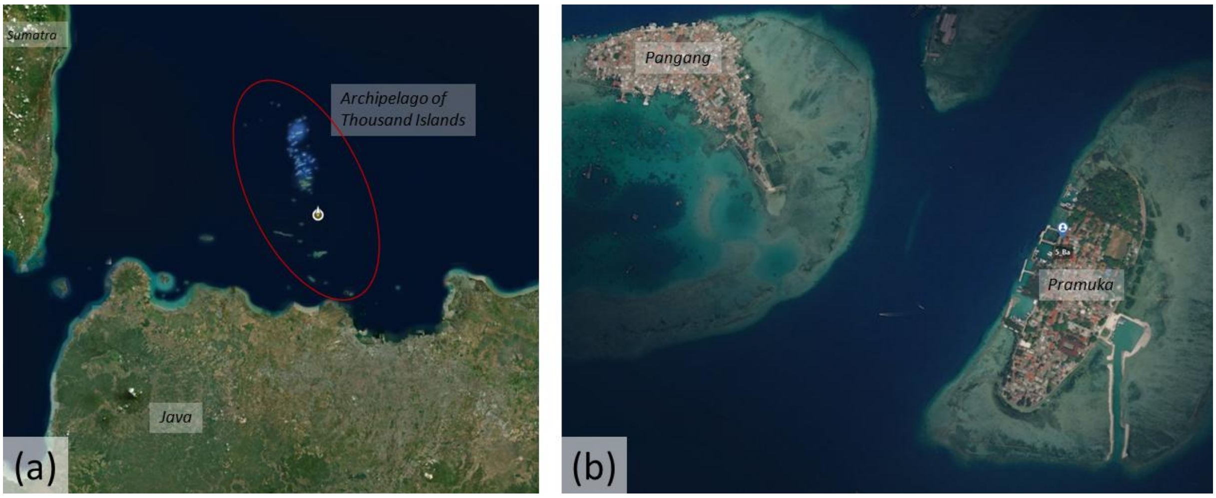

Fig. 1: (a) Location of the Thousand Islands Archipelago and (b) overview of the Islands Pramuka and Pangang [Qinertia, 2026].

The island Pramuka measures approximately 0.9 km from North to South and 0.4 km from West to East and reaches a maximum altitude of 2 m in relation to sea level. An overview of the island can be seen in the Figure 1 (b). Pramuka Island is inhabited by approx. 2000 people whereas most of the inhabitants work as fishermen [Hendarti, 2021]. Back in 1995, the Indonesian Department of Forestry declared the area around Pramuka as “Traditional Usage Sea”, meaning that this area can be used for research and education [Puspita at el., 2013]. A physico-chemical analysis of the water quality, which was conducted in November 2019 by Hermansyah et al., revealed a water temperature of 30 °C, a water transparency of 8 m and a coral coverage of 5.35 % within the Tanjung Elang Waters of Pramuka Island [Hermansyah et al., 2019]. Offering clear water conditions and natural as well as man-made test objects such as corals, reefs, ridges or peer structures in direct vicinity, the survey area around Pramuka Island offered adequate testing and data collection opportunities.

3. SENSOR TECHNOLOGY

To assess the potential of combined sensor approaches for a comprehensive underwater and shore mapping from shipborne and airborne data, the underwater laser scanner ULi developed by the Fraunhofer IPM, an MBES from Norbit and an airborne bathymetry laser scanner ABS from the Fraunhofer IPM, was used.

3.1 ULi

The underwater laser scanner ULi consists of two main components being (1) a housing which can be used in depths of 300 m and (2) a processing unit which is used for data acquisition.

To project the laser beam onto the underwater environment and detect the returning light, a green laser with a wavelength of 532 nm and two rotating wedge prisms, allowing for a 44 ° field of view, are used. While the laser has a pulse repetition rate of 100 kHz, the rotating prisms allow the entire field of view to be captured without moving the underwater laser scanner. Hence, the laser scanner can be operated in either linear or dynamic mode. For a dynamic application, the trajectory of the underwater laser scanner is tracked by an attached and calibrated Inertial Navigation System (INS) from SBG Systems which is connected with two GNSS antennas. The recorded trajectory can later be merged with the retrieved point cloud.

The final achievable precision and measurement range depends on the clarity of the water. While clear waters are supposed to allow scanning distances of several tens of meters and submillimetre precision, turbid waters apparently only allow for a measurement range of twice the secchi depth [Fraunhofer IPM, 2024].

3.2 MBES

The multibeam echosounder WBMS X from Norbit transmits acoustic waves with a frequency between 200 kHz and 700 kHz to collect bathymetric data in water depths of up to 100 m. By measuring the speed of sound in the water and the time it takes for a signal to be reflected and received by a receiving unit, the prevailing water depth is computed. With a ping rate of up to 60 Hz, a resolution of 0.9 ° x 0.9 ° for a frequency of 400 kHz and a resolution of 0.5 ° x 0.5 ° for a frequency of 700 kHz can be achieved. Besides, the system operates with a bandwidth of 80 kHz, resulting in an achievable depth resolution of < 10 mm [Norbit, 2025]. In combination with two GNSS antennas mounted on top of the echosounder, an RTK base station installed on Pramuka Island and a Njord multi-GNSS Receiver from SatLab, a precise georeferencing of the collected bathymetric data is achieved.

3.3 ABS

The airborne bathymetric laser scanner ABS is an active remote sensing technique which is used to measure topography and shallow water bathymetry by emitting and detecting laser pulses. Therefore, the ABS operates on the pulse-based Time-of-Flight principle. Here, the distance between the sensor and the target is determined from the two-way travel time of the laser pulse [Guenther, 1985; Irish & Lillycrop, 1999].

The ABS consists of an encoder, which projects a laser beam onto a tilted rotating mirror. The mirror allows for a full opening angle of 30 ° and a nearly elliptical scan pattern. Since the short-range ABS model uses a collimated laser beam, a footprint diameter of 5 cm at a flying altitude of about 20 m can be achieved [Fraunhofer IPM, 2025].

By simultaneously emitting a green and a red laser with a respective wavelength of 515 nm and 1030 nm at laser class 2M, a penetration into the sea surface as well as a reflection off the sea surface can be realized. In combination with an attached Quantra Micro, a high-performance GNSS-aided inertial navigation system from SBG Systems, the laser returns can be directly geo-referenced. Finally, the ABS offers a pulse repetition rate of 35 kHz and a measurement range of 1 secchi into the water [Fraunhofer IPM, 2025]. Since the ABS records the full waveform, a multi echo detection can be realized.

4. SET-UP

To conduct the ship-borne measurements, ULi and the MBES were each pole mounted onto a wooden boat, which can be seen in the Figure 2 (a) below.

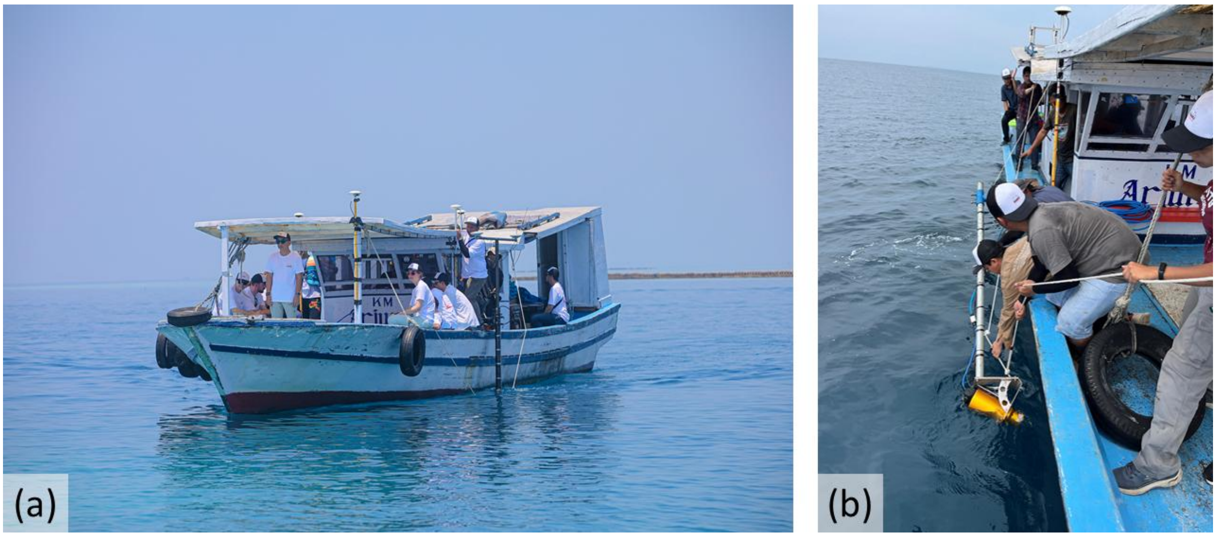

Fig. 2: (a) The wooden survey boat fully equipped with ULi on starboard side and the MBES on port side. (b) The scanning unit of ULi is mounted on a movable pole, facing a field of view underneath the ship.

While ULi was mounted on a movable pole on the starboard side, the MBES was fixed to a moveable pole on the port side. Both systems were operated fully independently and could be flexible moved up and down for safe mooring ashore and with regard to the prevailing survey requirements. The process of lowering the ULi to the water is displayed in the Figure 2 (b). The scanning unit of ULi was mounted pointing 30 ° tilted from the horizontal plane downward underneath the ship to port side to ensure a sufficient overlap with the MBES data. The GNSS antennas for the ULi system were set-up with a 2.59 m long baseline on port and starboard side on the rooftop of the vessel. Both antennas were directly connected to the ULi integrated SBG inertial navigation system. The GNSS antennas for the MBES system were set-up along track on top of the pole mounted Norbit system. After the remaining hard- and software was set-up on the vessel, calibration routines have been performed prior to survey. Hence, a patch-test routine was performed to calibrate the MBES and several eight shapes were driven to calibrate the inertial measurement unit of the ULi inertial navigation system.

The set-up of the ABS is depicted in Figure 3 below. As shown, the ABS was mounted on a DJI M350 drone, which contains four propellers and which offers a payload of 2.7 kg. The laser scanner has a length of 325 mm, a width of 155 mm, and a height of 165 mm [Fraunhofer IPM, 2025].

Fig. 3: ABS Configuration.

Equipped with a single GNSS antenna to not exceed the payload limitations and an inertial navigation system, which was specifically developed for UAV-based mapping tasks [SBG, 2025b], an accurate positioning solution and thus georeferencing of the data could be realized. To enable a precise sensor alignment and to enhance the overall system stability, a calibration procedure involving the manoeuvring of 8-shapes was performed before the data acquisition.

5. DATA ACQUISITION

For ULi, the processing unit was connected to a laptop and the entire operation and data acquisition steered over a graphical user interface. Here, a circular scan pattern, a motor speed of 30 Hz, a radius change speed of 0 Hz and a radius of 1 − offering a full field of view − was set. These settings result in a palmer scan pattern. The minimum range was set to 0.5 m and the maximum range to 20 m. Furthermore, the laser filter was set to None, which means that the data was collected in 3B full power mode.

The survey planning and the data acquisition for the MBES was conducted in the software EIVA NaviPac. Hence, the data was collected with an opening angle of 150 ° and a frequency of 400 kHz. To avoid the collection of near-field noise and enhance the bottom detection, the upper gate was set to 1 m and the lower gate to 50 m.

To design and execute the flight paths for the ABS, the Universal Ground Control Software was used. Overall, the survey was planned with a swath angle of 30 °, a flying altitude of 20 m, a side overlap of 40 % and a flight speed of 5 m/s. These general parameters were applied to optimize coverage and image quality. The flight lines were strategically designed from the coastline extending up to 200 m in the seaward direction. This configuration ensured a consistent spatial data collection across the coastal-to-marine transition zone. To filter out unnecessary data and thus reduce the overall amount of stored data, the range was set to 30 m and the skip distance to 5 m.

An overview of the collected data which will be evaluated in this paper is depicted in the following Figure 5. Subsequently, all data was collected on the slope along the coastline of Pangang Island.

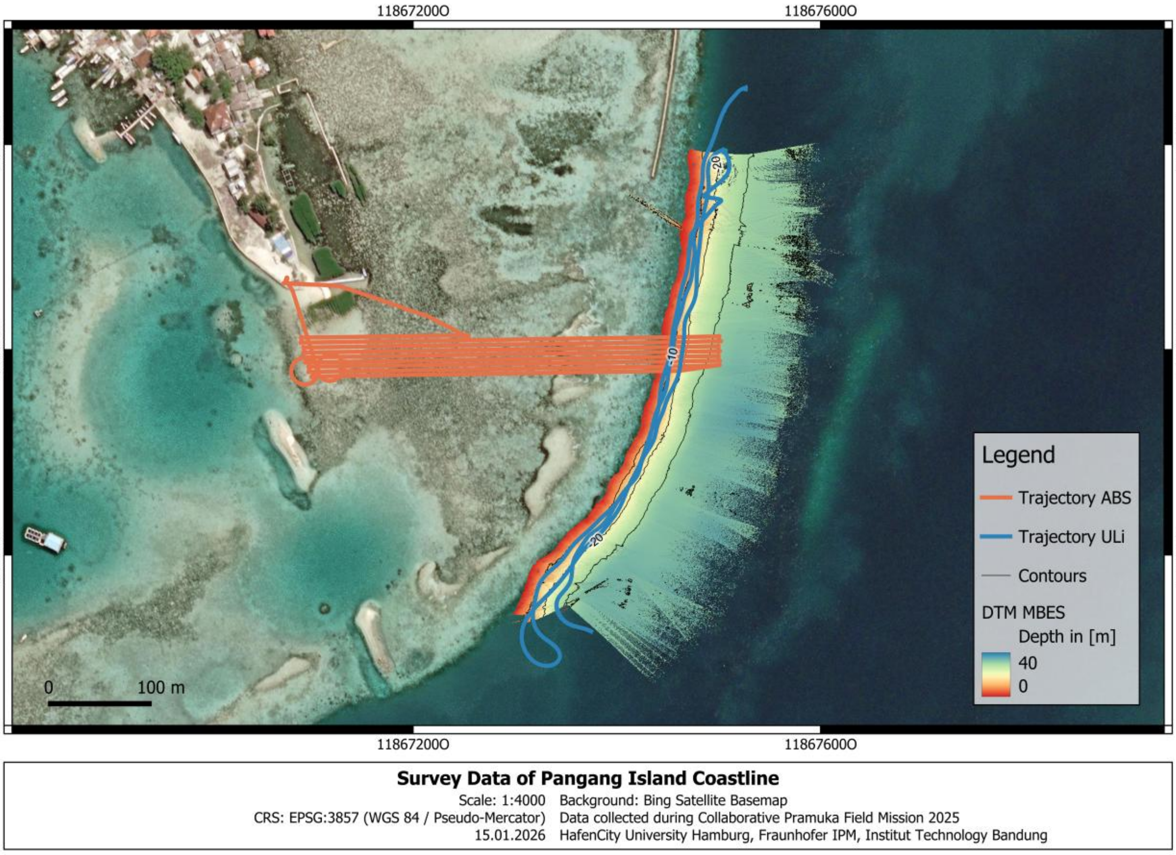

Fig. 5: Overview Map of the surveyed area.

6. PROCESSING

The data from ULi and the ABS are stored in a proprietary data format. To realize a georeferenced point cloud for both systems, a precise trajectory has to be computed. In this project, both systems only used a GNSS single point positioning solution. Hence, the INS data for the real-time navigation solution was gathered by processing the data in an Extended Kalman Filter [SBG, 2025a]. To improve the retrieved solutions, a post-processing navigation solution was determined with the software Qinertia from SBG Systems by applying a forward-backward-filter. Therefore, the GNSS data and the motion data are processed along with the data from the GNSS base station, which was set-up on Pramuka Island. Next to the navigation solution, the software is also able to estimate and improve the position offset between the INS and the GNSS antennas. The final navigation solution is imported to the software Pulsalyzer, which was developed by the Fraunhofer IPM. Here, the acquired scanner data is georeferenced by applying the previously known calibration parameters of the laser scanners, including for instance the position offset between the laser scanner and the INS or the refraction coefficient. The subsequent point clouds are further filtered to remove any noise or reflections within the water column. The resulting georeferenced point clouds were then further analysed in CloudCompare [CloudCompare, 2025]. Meanwhile, the MBES data were processed using the hydrographic data processing software QPS Qimera. Here, a digital elevation model with a grid cell size of 0.5 m x 0.5 m was generated. The cleaning of the data was carried out by using the slice editor and the 3D editor.

7. RESULTS

The first outcomes and results of the collaborative scientific project including data acquisition by the underwater laser scanner ULi, the Norbit multibeam echosounder and the airborne bathymetric laser scanner ABS, are presented below.

To examine the three sensors, different parameters were compared. The findings are presented in the following Table 1. Here, it becomes evident that the set-up time already greatly varies. Since the ULi and the MBES are ship-mounted systems, their set-up time can take up to several hours and is therewith much higher in comparison to the drone mounted ABS. Subsequently, the ULi and the MBES cannot be operated as flexible as the ABS. With regard to the actual data acquisition, ULi is able to achieve a higher point density than the MBES and the ABS. This suggests that ULi offers the highest spatial resolution among the compared sensors. Since the ULi and the ABS are optical systems, their measurement range depends on the clarity of the water. Subsequently, both systems have a limited depth range. For the collected data on the shoreline of Pangang Island, the reachable depth below the water surface for ULi was around 14 m. The MBES allowed for a full depth coverage and the ABS was able to penetrate roughly 12 m into the water. Therefore, the penetration depth of ULi and ABS, using optical waves, are quite similar but generally way shorter to what can be achieved by the propagation of acoustic waves with an MBES. The computed width of coverage for a depth of 10 m, comparably to the survey scenario, varies from 8.08 m for the ULi to 16.08 m for the ABS and 74.64 m for the MBES. Therewith, MBES offers the highest swath coverage. Taking the acquisition time alone and not the set-up time into consideration, the MBES can especially map larger areas within the shortest period of time. Due to the achievable point density, the data size and thus also the time to download the collected data greatly varies. The final processing time is highest for ULi and ABS. This can be related to the fact that the recorded trajectories have to be processed in Qinertia beforehand, then merged with the point cloud data in Pulsalyzer and finally evaluated in further point cloud software's such as CloudCompare. The MBES data can be processed within one software product. Furthermore, MBES processing is already much more advanced, offering a variety of different filter options as well as automated processes. Meanwhile, the processing of ULi and ABS data can currently only be done in very specific software solutions which are partly still in the development phase and which do not offer any automated approaches for optical point clouds retrieved under water yet.

Tab. 1: Comparative Parameters between all three used sensors.

Parameter	Sensor		
	ULi	MBES	ABS
Set-Up Time	High	High	Low
~ Point Density [along track [m] x across track [m]]	0.083 x 0.149	0.710 x 0.559	0.119 x 0.178
~ Reachable Depth below water surface [m]	14	full depth coverage	12
Width of Coverage [m] calculated for 10 m depth	8.08	74.64	16.08
Width of Coverage [m] measured for 10 m depth	8.10	-*	15.07
~ Data Size for one survey line	High (4.7 GB)	Low (70 MB)	Medium (1.2 GB)
Processing Time	High	Medium	High

*due to the sloping terrain, a full swath coverage in a water depth of 10 m only is not available.

Example screenshots of the ULi, MBES and ABS point clouds, collected along the slope of the coastline of Pangang Island, are presented in the Figure 6 below. As it can be seen in the ULi point cloud (a), a depth range of approximately 14 m was reached. The measured secchi depth in that area was around 13 m. In the MBES point cloud (b), one can see that the entire slope down to 40 m is covered. In the ABS point cloud (c), the red coloured points in the upper part refer to a reflection off the water surface caused by the red laser. The points underneath were collected from the green laser which penetrated roughly 12 m into the water. The screenshots on the right side of Figure 6 show close-ups of the respective point clouds from the left hand side to the scale level of 1 m. In the ULi point cloud (d) and the ABS point cloud (f) one can nicely recognize the palmer scan pattern, whereas the MBES point cloud (e) presents a clear line pattern with separate swath lines behind each other in along-track direction. In addition, it becomes evident, that the ULi and ABS point clouds show a high point density and already offer structural details, while the MBES resolution is not comparable and too low for small feature detection.

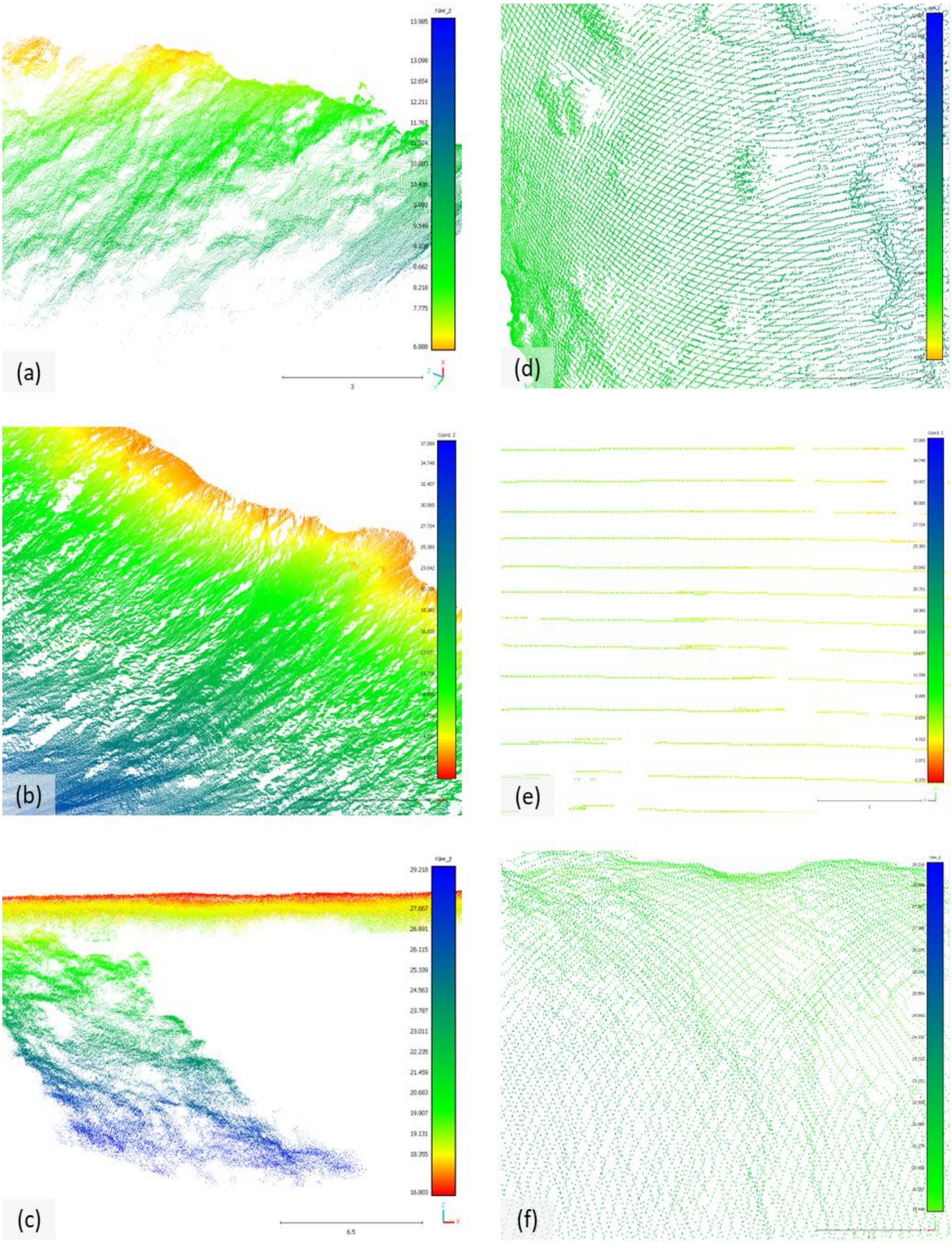

Fig. 6: Point clouds of the slope on the coastline of Pangang Island derived from (a) ULi, (b) MBES and (c) ABS. (d), (e) and (f) show close-ups of the same point clouds to 1 m scale. All point clouds are coloured by depth [m].

8. CONCLUSION AND OUTLOOK

The retrieved point clouds from the survey area along Pangang island show, that the underwater laser scanner ULi and the airborne bathymetric laser scanner ABS offer a shorter along- and across-track distance and therewith also a supposedly higher resolution than the MBES system. As a result, the optical point clouds offer a higher spatial detail and surface fidelity. This however only applies in the clear and shallow waters until a depth of about 10 m where optical propagation remains effective. In addition, it can be concluded that ULi and the ABS can reach a penetration depth which roughly equals 1 secchi depth.

Future works will focus on the collection and evaluation of further datasets collected by the simultaneous operation of acoustic and optic sensors. Furthermore, the airborne survey system will be enhanced by integrating a hyperspectral camera alongside the existing bathymetric laser scanner. This enhancement is expected to enable the concurrent acquisition of high-resolution spectral information and thus improve the precision of environmental mapping and analysis. The hyperspectral data will further serve as a source of ground-truth information for the calibration and validation of laser-derived measurements. In addition, upcoming research works will also explore the capabilities of automatic seabed classification using a combined approach of MBES backscatter data, ULi data, ABS data and hyperspectral imagery. Integrating these modalities is expected to enhance classification accuracy and support more detailed marine habitat mapping.

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