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Historic Shipwreck Study in Dongsha Atoll with Bathymetric LiDAR

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ABSTRACT Dongsha Atoll is a coral reef located in the South China Sea. The surrounding area is characterized by dangerous shoals. Historic shipwrecks mark past human activities. Due to the shallow water and risky navigational conditions in the area, a sonar survey with platforms on the water surface was not feasible. Airborne bathymetric LiDAR, which utilizes green laser for measurement, however, is a proven convenient method for studying shipwrecks around the atoll, particularly in shallow-water areas. At a point density of about 3.5 m by 3.5 m, four shipwrecks were identified. The bathymetric measurements allow not only the length of the shipwreck to be estimated, but also its height above the sea floor. The full waveform record of the laser reflection also provided information to separate the wreckage from its surroundings. This provides an excellent working environment for marine archaeological analysis, as not only the location, but also the depth and geomorphological information can be assessed in an integrated setting. Copyright © 2013 John Wiley & Sons, Ltd.

Key words: Underwater archaeology; bathymetric LiDAR; South China Sea; waveform; remote sensing; coral reef

Introduction

Due to its remote location and being under military management, archaeological research on Dongsha Atoll is quite limited in. Based on an investigation of the ecological environment, the process of development of the islands and previously discovered artefacts, three surveys have been successfully conducted, including the discovery of the 'Dongsha Ruins' site (Chen, 1997). Within the site, objects such as porcelain sherds, pottery, charcoal, iron nails and ironware, as well as shells and guano, have been uncovered, indicating that these are remnants of the activity of Chinese fisher folk. In addition to the cultural heritage on land, there are a number of shipwrecks in the Dongsha area. Pickford (1995) documented seven ships sunk in the Dongsha area between 1609 and 1863, including *Utrecht*, *Frederik Adolphus*, *Singular*, *City of Shirez*, *Phantom*, *Georges Sand* and an unidentified ship. With the support from the Construction and Planning Agency of the Taiwan Government, Chiau *et al*. (2005) conducted an underwater cultural heritage study. This project was focused on shipwrecks and other isolated objects in the region.

In order to explore the airborne bathymetric LiDAR technology, and collect detailed sea-floor terrain information for Dongsha Atoll, the Ministry of Interior of Taiwan supported a project utilizing this technology for mapping Dongsha Atoll. This project has two major objectives. The first is to evaluate this technology, and develop a strategy on adopting this technology for future mapping of shallow-water areas. The other is to establish sea-floor terrain information for various marine research projects in Dongsha. In Dongsha, typhoons usually occur in summer and strong winds are experienced in winter. Due to its specific location and weather conditions, research in Dongsha is always challenging.

The number of applications of airborne LiDAR for archaeological prospection is growing. Specific visualization and analysis schemes have been developed for this purpose (Bennett *et al.*, 2012; Challis *et al.*, 2011; Hesse, 2010; Kokalj *et al.*, 2013), but,most use topographic LiDAR systems and the study sites are on land. In this study, an application of airborne hydrographic LiDAR (AHL; also known as ABL,

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Airborne Bathymetric LiDAR) is reported. The AHL uses green laser and is designed for bathymetric survey. Application of AHL for archaeological prospection has been undertaken by Doneus *et al*. (2013) and Prahov *et al*. (2011). In this study, the potential of AHL for historic shipwreck studies is explored.

Bathymetric LiDAR

Airborne bathymetric LiDAR has made significant progress in recent years. JALBTCX (2011) provides a good collection of the documents. The most widely applied underwater sensors for shipwreck searches include side-scan sonar systems, sub-bottom profilers, multi-beam depth sounding systems and marine magnetometers. For example, Boyce *et al*. (2009) used a Marine Magnetics Seaspy (Overhauser) marine magnetometer and a Garmin 200 kHz echo sounder. Plets *et al*. (2008) reported the use of three-dimensional Chirp sub-bottom profiler. All of these systems were operated from surface vessels, but terrain and navigation limitations are major factors that restrict bathymetric survey from surface vessels.

Bathymetric LiDAR originated from laser detection of underwater objects (Guenther and Goodman 1978; LaRocque and West 1990). The current system includes a laser ranging device, a scanning mechanism and a direct georeferencing system. A digital imaging device usually accompanies the bathymetric LiDAR system in operation, which provides additional information for data editing. Typically, bathymetric LiDAR is utilized for detecting the sea bottom in shallow coastal waters (< 50 m). A green laser with a wavelength of 532 nm is used for penetrating water to measure the sea floor. Although the water surface could be identified from the waveform of the green laser reflection/scattering, an infrared channel (1064 nm) and the Raman channel (645 nm) provide more reliable and accurate identification and measurement of the water surface. Due to the consideration of different signal strengths resulting from different water depths, the green laser return is digitized with two receivers. One is for the deep channel, the other for the shallow channel. The laser scanner used in the Dongsha Atoll survey has multiple channels, including one infrared channel, two green channels and one channel for Raman scatter. This system is also equipped with a topographic LiDAR, which operates on the infrared channel only. The laser scanner simultaneously collects 4 kHz bathymetric and 64 kHz topographic LiDAR soundings, and digital images acquired at 1 Hz cover the LiDAR scanned area. A IDE UI-2250SE digital camera was used with 1200 × 1600 pixel resolution and focal length of 12 mm. Full waveform information is stored for the bathymetric laser (Henrik, 2006).

The laser fired from the laser scanner maintains a forward angle from nadir, which is close to 20º. This can avoid direct reflection from the sea surface. The laser scanner system principle is shown in Figure 1, where V is the flying direction, θ is the forward angle,

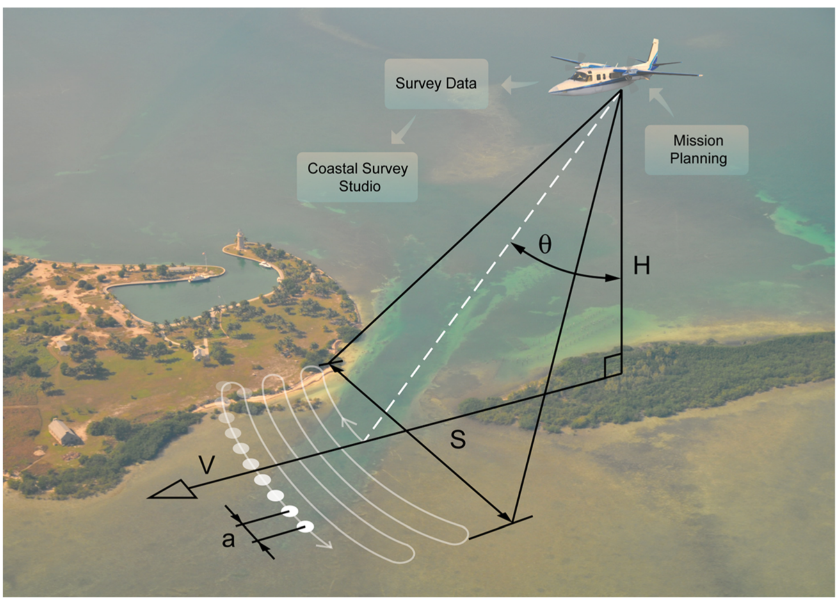

Figure 1. AHAB HawkEye II system principle. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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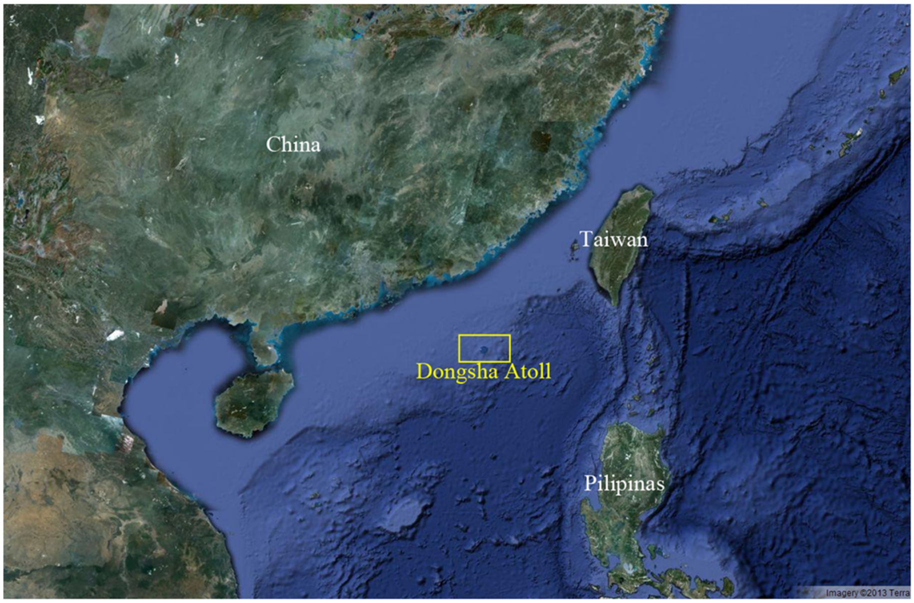

Figure 2. The location of Dongsha Atoll (retrieved on 20 May 2013 from http://maps.google.com.tw). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

S is the swath width, *a* is the point spacing and *H* is the flying height. In general, it applies a one-dimensional scanning mechanism.

Case study

The study site is Dongsha Atoll. 'Dongsha' literally means 'East Sands' in Chinese. The name originates from numerous submerged reefs in the area. Relative to the other three 'sands', Nansha (South Sands), Chungsha (Middle Sands) and Shihsha (West Sands), Dongsha is in the East. Dongsha Island is the only land above water year-round in this atoll, and is also known as Pratas Island. This island is located about 20.7018° N,116.7266°E, which is about 240 nautical miles from Kaohsiung, Taiwan, 230 from Penghu, 170 from Hongkong, 140 from Shantou and 420 from Manila (Figure 2). This geographical setting makes Dongsha an important site for both sea transportation and fisheries. Dongsha and the South China Sea both lie on the path of the maritime silk-road (Jacq-Hergoualc'h, 2002; Li, 2006). Because this completely developed coral atoll features a rich marine life and unique geographical and ecological features, Dongsha Atoll was designated as a national park in 2007.

LiDAR data processing and Dongsha survey result

In late September of 2010, a bathymetric LiDAR survey was conducted for the complete Dongsha Atoll. Contrary to shipborne sensors, bathymetric LiDAR is airborne and is free from the navigation risk imposed by shoals. Airborne bathymetric LiDAR is not a common technology. At present, there are only four companies commercially manufacturing airborne bathymetric LiDAR systems, namely, Airborne Hydrography AB (AHAB) from Sweden, Optech Inc. from Canada, Fugro (Tenix) LADS from Australia, and RIEGL from Austria. The instrument used in the 2010 survey was a Hawkeye II manufactured by

Table 1. Survey parameters for Dongsha Atoll.

Parameter	Mission 1	Mission 2
Spot spacing (m)	3.5 × 3.5	2 × 2
Flight altitude (m)	400	300
Survey speed (knots)	150	150
Swath width (m)	160	120
Area (km^2)	450	20
Total flight lines	203	26
Flying hours (h)	22	6
Bathymetric soundings per second	4000	
Topographic soundings per second	64000	

Table 2. Validation results for Dongsha Atoll.

Evaluation approach	ALB-SB
Points	80 630
Mean difference (m)	−0.51
Standard deviation (m)	0.44
Max Absolute Difference (m)	2.85
Points of difference < 0.5 m (%)	58.56
Points of difference < 1 m (%)	82.81

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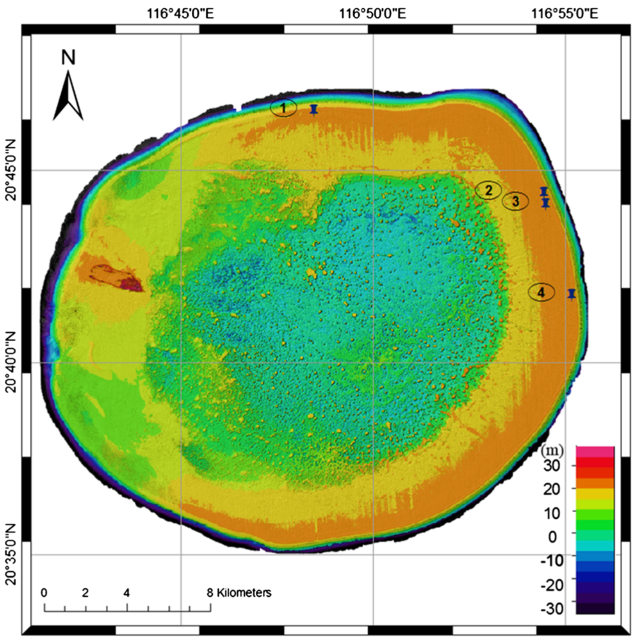

Figure 3. The four possible shipwrecks from bathymetric LiDAR survey. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

AHAB. The point density of the survey is about 3.5 m by 3.5 m (Shih *et al.*, 2011). With this dataset, the shipwrecks are studied from both bathymetric and photographic information.

The aerial survey was conducted during the day time of 22–25 September 2010. In total, 229 flight lines were flown. The survey parameters are listed in Table 1. In addition to the 3.5 m density for the entire atoll, a further 20 km^2 area located in the east portion of the atoll was surveyed with a 2 m density. Dongsha Airport was used as the base of operations. A Swearingen SA-226 T aircraft was used as the flying platform. In order to reduce the sun glint influence, the flight direction was chosen to be north–south. Two cross lines, in the east–west direction, were flown for data validation.

Data were processed using AHAB's CSS, Fledermaus and GreenC software packages. The CSS processing uses the position and orientation information, along with the LiDAR return and waveform information to compute three-dimensional positions of each data point on the ellipsoid height system. The data points are then reviewed and cleaned in Fledermaus while viewing the associated waveform and digital camera imagery with GreenC. After consolidating all of the information, there are 46 908 917 measured points (waveforms) in the 450 km^2 area. Data validation is conducted with an overlap between both the parallel lines and the cross lines. The accuracy meets the specification of IHO S44 class 1b (IHO, 2008). That is, one standard deviation is less than 25 cm. Eleven square kilometre sonar measurements were also made for additional data validation (Shih *et al.*, 2011). All measurements are in good accordance.

For bathymetric LiDAR data validation of Dongsha Atoll, sonar survey were conducted after data acquisition. Because of the different footprint of LiDAR and sonar, the flat seabed should be selected for validation. The interval between the survey lines is about 40 m, and the interval of cross lines is 500 m at Dongsha Atoll for internal accuracy check. Due to the same reason, the survey area at Dongsha Atoll is almost in the southern Dongsha island. In March 2011 the total survey area was about 14 km^2. The difference statistics are shown in Table 2. The mean difference is about 50 cm and the sonar surface is higher than the LiDAR data. This situation may be caused by the topography

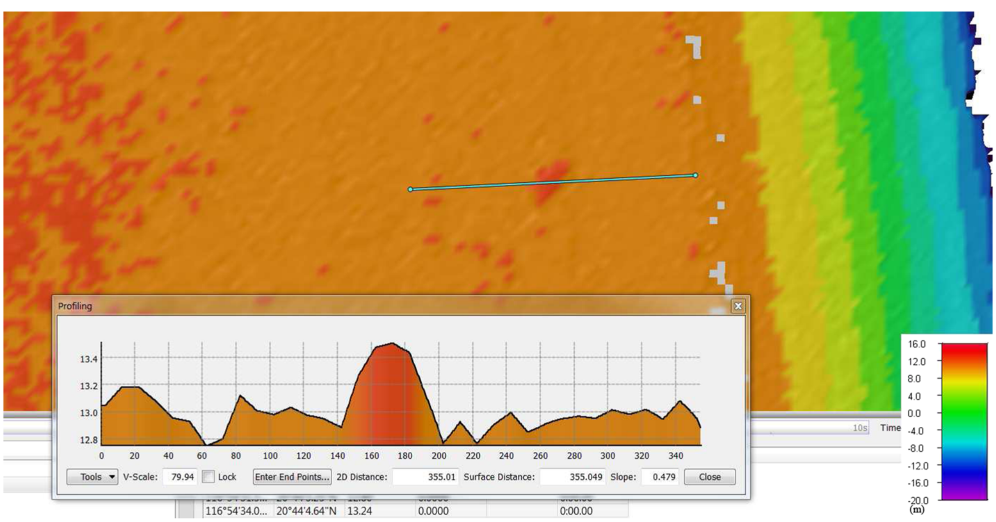

Figure 4. The profile of Target 4 (north is towards the top). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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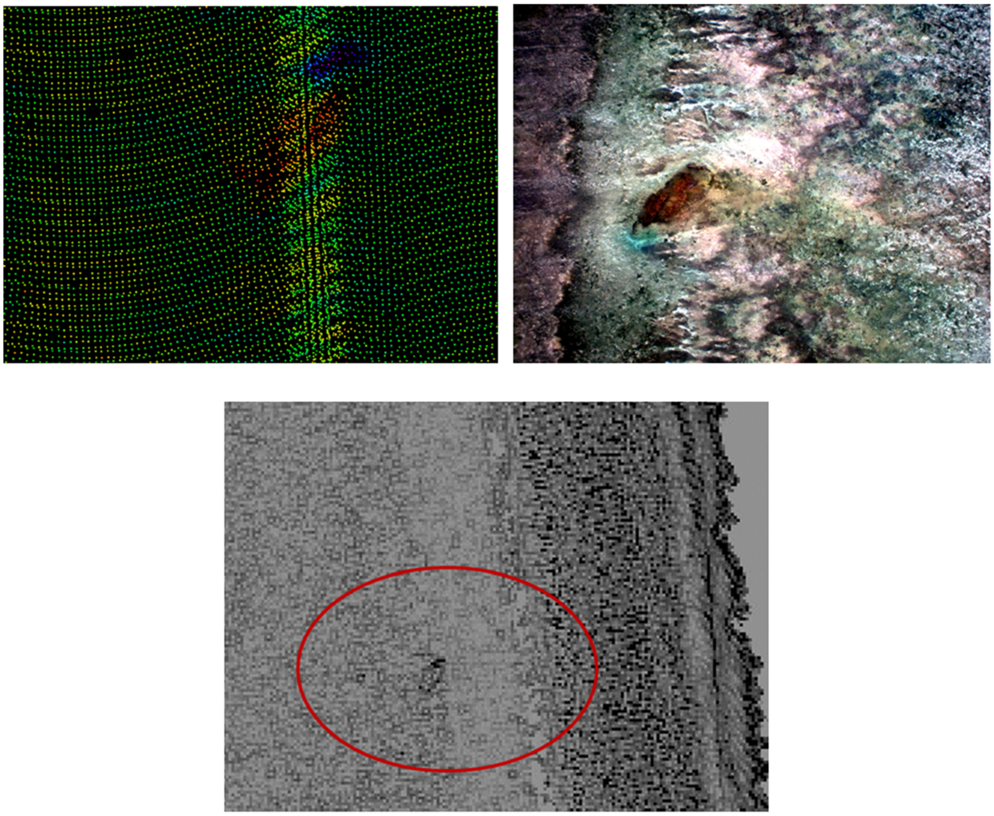

Figure 5. (a) The top view of Target 4; (b) digital image of Target 4 (c) Accessibility from the bathymetric model. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

of Dongsha Atoll, which changes greatly, and the different footprint of sonar and LiDAR.

Shipwrecks identified from bathymetric LiDAR

The identification of shipwrecks was made by human interpretation during editing point clouds with aerial photographs. From the bathymetric LiDAR survey, four possible ship wrecks were found (Figure 3): all four are on the reef flat. The identification of the shipwrecks was mainly performed by observing the digital images taken with a small format frame camera during the airborne LiDAR survey. Then, the length, width and height could be measured from both the airborne image and LiDAR

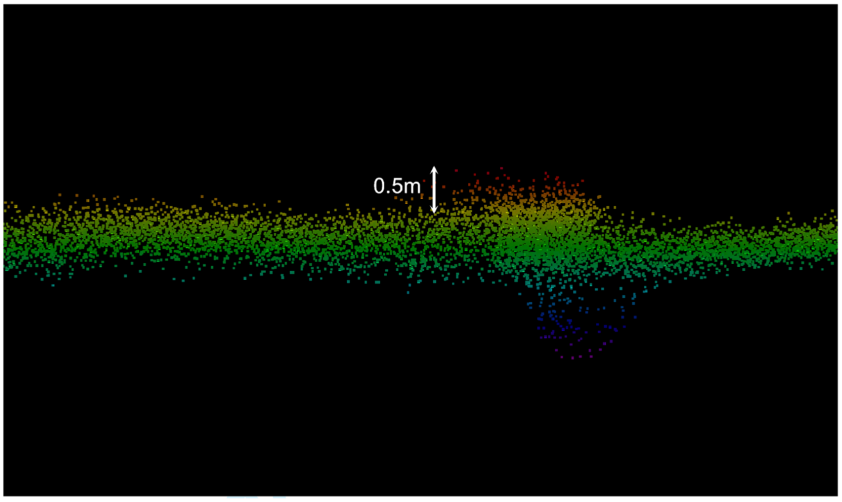

Figure 6. The side view of Target 4. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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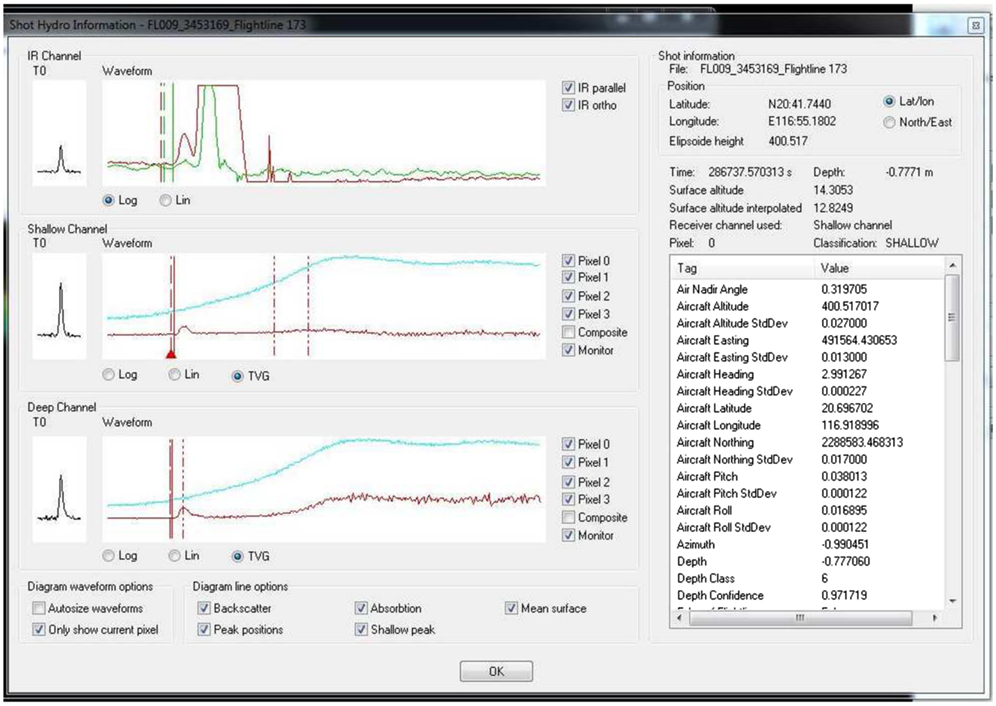

Figure 7. The waveform of Target 4. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

point cloud. Due to the similarity between cases, only the figures related to Target 4 are included in this article.

From the profile, the height anomaly caused by the shipwreck could be identified (Figure 4). Bathymetric side-view, accessibility, sky-view, trend removal and LiDAR waveform are all helpful in providing additional information on the shipwrecks (Figures 5–7). From the survey result, not only could the length and width be measured, but also the height of the shipwreck above the sea floor. The parameters identified for these four targets are listed in Table 3. The reflectance of the ship's surface material could also be derived from the waveforms. This could provide even more information about the shipwreck. It was also revealed that the digital image was far more helpful in identifying the shipwrecks, but the LiDAR measurements provided more quantitative information. The existence of the four shipwrecks identified in this study were confirmed by the Ministry of Culture (2011) based on field reconnaissance.

Shipwrecks identified from side-scan sonar

After surveying the literature in Chinese and in other languages, 28 recorded shipwrecks could possibly be located in the region. With side-scan sonar, Chiau *et al.* (2005) identified 11 possible shipwrecks at nine sites in this region.

The depth range of bathymetric LiDAR is largely influenced by water turbidity and sea-bed reflectance, as well as limitations originating from the system characteristics, such as laser energy and detector sensitivity. Water turbidity is usually measured with a Secchi-disk reading. The nominal penetration capability of Hawkeye II is 3× Secchi depth. At Dongsha Atoll, the water clarity is high and the limitation of water depth with the laser scanner is about 50 m. The bathymetric LiDAR operation is also influenced by the water surface condition. A rough surface and white water would generate difficulties. Therefore, the survey of 2010 was conducted in September during the best season of a year. The entire atoll was successfully mapped. All 11 targets identified by Chiau *et al.* (2005) are located in the outer part of the atoll, which is beyond the range of bathymetric LiDAR.

The 11 possible targets of shipwrecks identified in Chiau *et al.* (2005) are shown in Figure 8. The background is a depth-coded colour map of the digital bathymetric model produced from the bathymetric

Table 3. Measurements for the four targets.

Target	Length (m)	Width (m)	Height (m)
1	43.3	10.0	1.5
2	29.5	10.5	2.0
3	35.6	8.0	1.0
4	44.7	17.2	0.5

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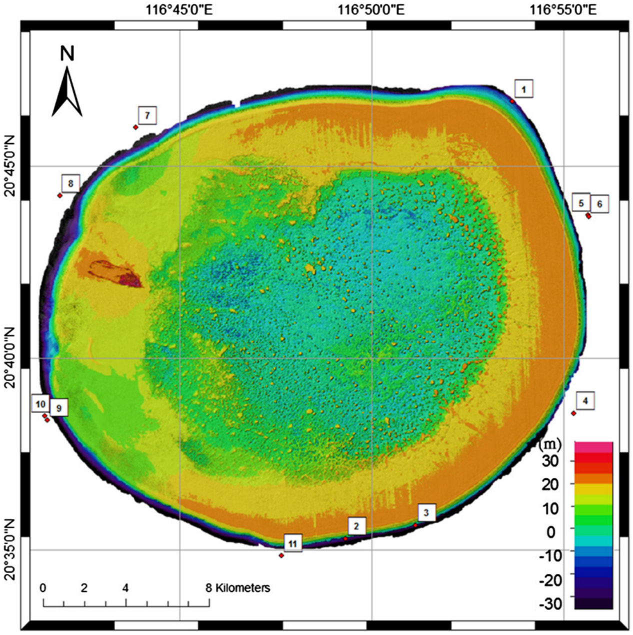

Figure 8. The locations of 11 possible shipwrecks from sonar survey. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

LiDAR survey. Most shipwrecks are located in the relatively deeper water area, beyond the navigational limitations of surface research vessels, and sites 4–11 are out of the bathymetric LiDAR survey region.

The identification of shipwrecks was made by human interpretation from the images formed by side-scan sonar. From these examples it can be seen that interpretation is not an easy task, however, both the horizontal and vertical size of the shipwrecks could be estimated from the survey.

Conclusion

This study reveals that bathymetric LiDAR is an effective tool. Whereas the detecting devices operated from surface vessels are limited by the navigational conditions, airborne bathymetric LiDAR provides an efficient and convenient way of surveying, particularly in shallow-water areas. Although the spatial resolution is 3.5 m in the current study, which limited the capability for detecting smaller wrecks, the coming generation of bathymetric LiDAR is expected to reach much higher spatial resolution. The specification of the Coastal Zone Mapping and Imaging Lidar (CZMIL) project product requirement requested the identification of 2 m × 2 m × 2 m navigation hazards (Macon, 2011). Therefore, airborne bathymetric LiDAR could provide an even more promising tool for shipwreck identification and marine heritage studies. With the dataset produced by AHL, systematic archaeological analysis could then be performed. In this study, AHL was used to measure length, width and height from the shipwrecks. Although AHL is capable of identifying shipwrecks, it was easier to find and identify them in the aerial images acquired during the AHL mission under the particular condition of this study, but AHL was found useful in confirming the shipwrecks identified.

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References

Bennett R, Welham K, Hill RA, Ford A. 2012. A comparison of visualization techniques for models created from airborne laser scanned data. *Archaeological Prospection* **19**: 41–48. DOI: 10.1002/arp.1414.

Boyce JI, Reinhardt EG, Goodman BN. 2009. Magnetic detection of ship ballast deposits and anchorage sites in King Herod's Roman Harbour, Caesarea Maritima, Israel. *Journal of Archaeological Science* **36**(7):1516–1526.

Challis K, Forlin P, Kincey M. 2011. A generic toolkit for the visualization of archaeological features on airborne LiDAR elevation data. *Archaeological Prospection* **18**: 279–289. DOI: 10.1002/arp.421.

Chen CY. 1997. A preliminary archaeological survey of the Dongsha and Nansha Taiping Islands. *Bulletin of the Institute of History and Philology Academia* **68**(2): 449–502. (In Chinese.)

Chiau WY, Chen YY, Hsieh HH. 2005. The Investigation of Ancient Ship Wrecks in the Dongsha Area. Construction and Planning Agency: Taiwan. (In Chinese.)

Doneus M, Doneus N, Briese C, Pregesbauer M, Mandlburger G, Verhoeven G. 2013. Airborne laser bathymetry – detecting and recording submerged archaeological sites from the air. *Journal of Archaeological Science* **40**: 2136–2151.

Guenther GC, Goodman LR. 1978, Laser applications for near-shore nautical charting, *Proceedings of SPIE Ocean Optics V* **160**: 174–183.

Henrik K. 2006. *HawkEye II Technical Description*. Airborne Hydrography AB; Jonkoping, Sweden

Hesse R. 2010. LiDAR-derived local relief models – a new tool for archaeological prospection. *Archaeological Prospection* **18**(2): 67–72. DOI: 10.1002/arp.

IHO. 2008. *IHO Standards for Hydrographic Surveys*, 5th edn. Special Publication No. 44, International Hydrographic Bureau; Monaco Cedex. http://www.iho.int/iho_pubs/standard/S-44_5E.pdf.

Jacq-Hergoualc'h M. 2002. *The Malay Peninsula: Crossroads of the Maritime Silk Road (100 BC-1300 AD)*, translated by Victoria Hobson. Brill Academic Publishers; Leiden; 749 pp.

JALBTCX. 2011. Publications. https://shoals.sam.usace.army.mil/Publications.aspx (accessed on 2 April 2011).

Kokalj Ž, Zakšek K, Oštir K. 2013. Visualizations of Lidar derived relief models. In *Interpreting Archaeological Topography, Airborne Laser Scanning, 3D Data and Ground Observation*, Opitz RS, Cowley D (eds). Occasional Publication 5 of the Aerial Archaeology Research Group, Oxbow Books: Oxford; 100–114.

LaRocque PE, West GR. 1990. Airborne laser hydrography: an introduction. *Proceedings, ROPME/PERSGA/IHB Workshop on Hydrographic Activities in the ROPME Sea Area and Red Sea*, October 24–27, Kuwait City. http://www.jalbtcx.org/downloads/Publications/28LaRoque_West_99.pdf (accessed 14 December 2009).

Li Q. 2006. *Maritime Silk Road*, translated by William W. Wang. China Intercontinental Press: Beijing, China; 194 pp.

Macon CL. 2011. *Coastal Zone Mapping and Imaging Lidar (CZMIL) Development Update*. International Lidar Mapping Forum 2011: New Orleans, LA.

Ministry of Culture. 2011. *The Second Phase Inventory of Underwater Cultural Assets Near Taiwan in 2011*. Ministry of Culture: Taiwan. (In Chinese.)

Pickford N. 1995. *The Atlas of Ship Wrecks and Treasures: The History, Location, and Treasures of Ships Lost at Sea*. DK Publishing, Inc.: New York.

Plets RMK, Dix JK, Adams JR, *et al*. 2008. The use of a high-resolution 3D Chirp sub-bottom profiler for the reconstruction of the shallow water archaeological site of the Grace Dieu (1439), River Hamble, UK. *Journal of Archaeological Science* **36**(2): 408–418.

Prahov N, Angelova H, Kotsev A, Popov A, Dimitrov S. 2011. Predictive modeling in archaeology: world practice and Bulgarian perspectives. *Bulgarian e-Journal of Archaeology* **1**: 71–121.

Shih PTY, Dushan A, Shyue SW. 2011. Bathymetric Lidar survey of Penghu Islands and Dongsha Atoll. *Sea Technology Magazine* **November**: 42–45.