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Coastal archaeology combines research in different environments: land surface, intertidal zone and sub-aquatic area. In consequence of the use of different archaeological methods for these different physical environments, there is a border between land and underwater zones. Archaeological topographic research is mainly confined to land surfaces and intertidal zones. This is unfortunate since knowledge of offshore underwater topography is essential to understand the organisation and distribution of sites on islands and coastal zones. Bridging the "border" between land and water in archaeological topographic research therefore requires the development of new archaeological documentation methods.

The latest technique to combine terrestrial and underwater survey is Airborne Laser Bathymetry (ALB), which utilizes a green, water-penetrating laser and therefore can be applied for mapping surfaces under shallow water. Depending on the water clarity these systems can provide a detailed characterization of the underwater topography and even be used to prospect archaeological sites under shallow water.

The presented paper will discuss the actual available ALB hardware and possibilities and limitations of the bathymetric sensor technique using sample data sets in Croatian case study areas in the northern Adriatic Sea. Maritime archaeological prospection is being tested in this area to provide high quality topographic mapping for later research questions regarding the rise and decline of settlements due to the changes in the shipbuilding, topography and navigational routes/natural harbours, and topography and harbour organisation.

Keywords: *airborne laser scanning, airborne laser bathymetry, archaeological prospection, underwater, submerged site, Roman villa, Mediterranean; northern Adriatic*

Introduction

Croatia is well known for its Mediterranean coastline, which has a length of more than 6.000 kilometres including the shorelines of its more than 1.200 islands. Coastal, intertidal and inshore areas are extremely rich in archaeological information content, including harbour sites, trading centres, coastal settlements, or industrial sites on the land surface. In the shallow water zone, shipwrecks, fish traps, middens, pile dwellings, weirs, wharves, docks, piers and other maritime infrastructure, various forms of dredging, oyster beds, individual larger objects (e.g. stone anchors), and any kind of submerged structure can be found.[1] Therefore, the boundary between land and water plays an important role in archaeological research and investigations of this environment play a particular important role in Croatian archaeology.

The archaeological investigation of coastal areas is therefore usually divided into two environments: land surface and underwater zones, which are combined by an intertidal area. Topography is an important link between these zones. A detailed knowledge of the topography is therefore essential for understanding of any archaeological site or landscape. This fact is especially important for the archaeological heritage in the Mediterranean region, because coastlines have changed due to sea-level rise[2] and many former coastal sites are now submerged in shallow water (depth less than a few metres). Mapping the relief within these areas is therefore important in order to be able to reconstruct former coastlines, identify sunken archaeological structures and recognize navigable areas which can help to locate potential former harbour sites.

Surprisingly, until now archaeology has lacked suitable methods to provide detailed maps combining the archaeological information of both land and underwater surface. This is obviously due to the difficulties, both environments pose on any archaeological documentation technique:

On land, the Mediterranean vegetation poses a specific challenge for any archaeological prospection technique. It is often Macchia that is considerably low, extremely dense, and contains a high amount of evergreen plants. At present there is no prospection method for the systematic discovery of buried sites in this environment. Fortunately, micro and macro topographic earthwork features tend to be well preserved in these areas, due to the stabilizing effect of vegetation on erosion processes and the lack of sufficient disturbance through mechanical action (such as ploughing). They are also visible from the ground and can be mapped using traditional surveying techniques: however, a woodland environment can make survey difficult and features may be obscured by brushwood and scrub. Conversely, low (micro topographic) earthworks, especially when covered with dense vegetation, are practically invisible from the air and can be difficult to locate on the ground even by an experienced surveyor.

The shallow water zones pose another problem to current archaeological survey. Due to practical constraints (boat access in areas of extremely shallow water) and depending on the pulse length, waterborne echo sounding has its limitations at shallow water depths.[3] Terrestrial surveys in water depths of up to three meters are extremely time-consuming, small-scale, and do not feature the necessary detail.[4] Airborne Laser Scanning (ALS) systems[5], used to produce accurate and precise terrain models of land surfaces[6], do not penetrate the water column, because the wavelengths that are typically used are in the Near-Infrared (NIR; 1064 nm) and Short Wavelength Infrared (SWIR; 1550 nm) are almost completely absorbed by water (Fig. 1). Airborne photogrammetry has been applied[7] and although it proves to be a relatively low-cost method that can be used for mapping large areas, its success is strongly depending on water transparency and characterised by many other specific weaknesses.[8]

To detect, document, visualise and archaeologically interpret coastal topography and its archaeological remains in Croatia, an applicable technique would therefore have to fit following requirements: (1) it has to cover large areas in a sufficiently short time; (2) in order to identify archaeological structures, the resulting digital terrain model (DTM) or digital depth model (DDM)[9] should have high detail (sub-meter); (3) it should both measure the topography on land covered with dense and low vegetation as well as under water, and (4) the depth range should be from the water surface to a few meters below.

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[1] Blondel 2009; Bowens 2009; Strachan 1995.

[2] Lambeck et al., 2004.

[3] Jong, 2002, p. 322.

[4] Bowens 2009, p. 91-95.

[5] Wehr, Lohr 1999.

[6] Crutchley 2010.

[7] Carbonneau et al. 2006; Marcus, Fonstad 2008, Westaway et al. 2001.

[8] See Carbonneau et al. 2006 for a discussion.

[9] Collin et al. 2008

Fig. 1: Near-Infrared aerial photograph of the harbour in Osor. Because electromagnetic Near-Infrared wavelengths are almost completely absorbed by water, the sea is rendered black.

In this paper, we will present a technique, which has the potential to fulfil these requirements: the latest generation of airborne laser bathymetry (ALB) scanner systems which are now becoming available will meet the aforementioned necessary requirements.[10] They have the potential to measure both land and underwater surfaces over large areas in high detail using very short and narrow green laser pulses, even revealing sunken archaeological structures in shallow water. Following our argument, this paper will present the latest generation of airborne bathymetric laser scanning systems and present results from various Croatian case-study areas in the northern Adriatic.

Airborne Laser Bathymetry (ALB)

Airborne Laser scanning (ALS, also referred to as airborne LiDAR) is a widely used data acquisition method for topographic modelling. During the last decade, it had a huge impact on the archaeology of forested areas.[11] The advantage of ALS is that the active laser is able to provide information on the topography below the tree canopy, resulting in dense and precise digital terrain models (DTM). Especially full-waveform (FWF) ALS systems show considerable advantages for the generation of DTMs in vegetated areas, as the FWF-parameters might improve classification of ALS data into terrain and off-terrain points, resulting in greater DTM quality and higher potential for the subsequent archaeological interpretation.[12]

So far, ALS proved to be extremely successful in Central and Northern European deciduous[13] and conifer[14] forests, as well as in the jungle of Central America[15].

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[10] See also Doneus et al. 2013.

[11] Devereux et al. 2005; Sittler 2004.

[12] Doneus, Briese 2011.

[13] Bofinger, Hesse 2011.

[14] Risbøl et al. 2006.

[15] Chase et al. 2010.

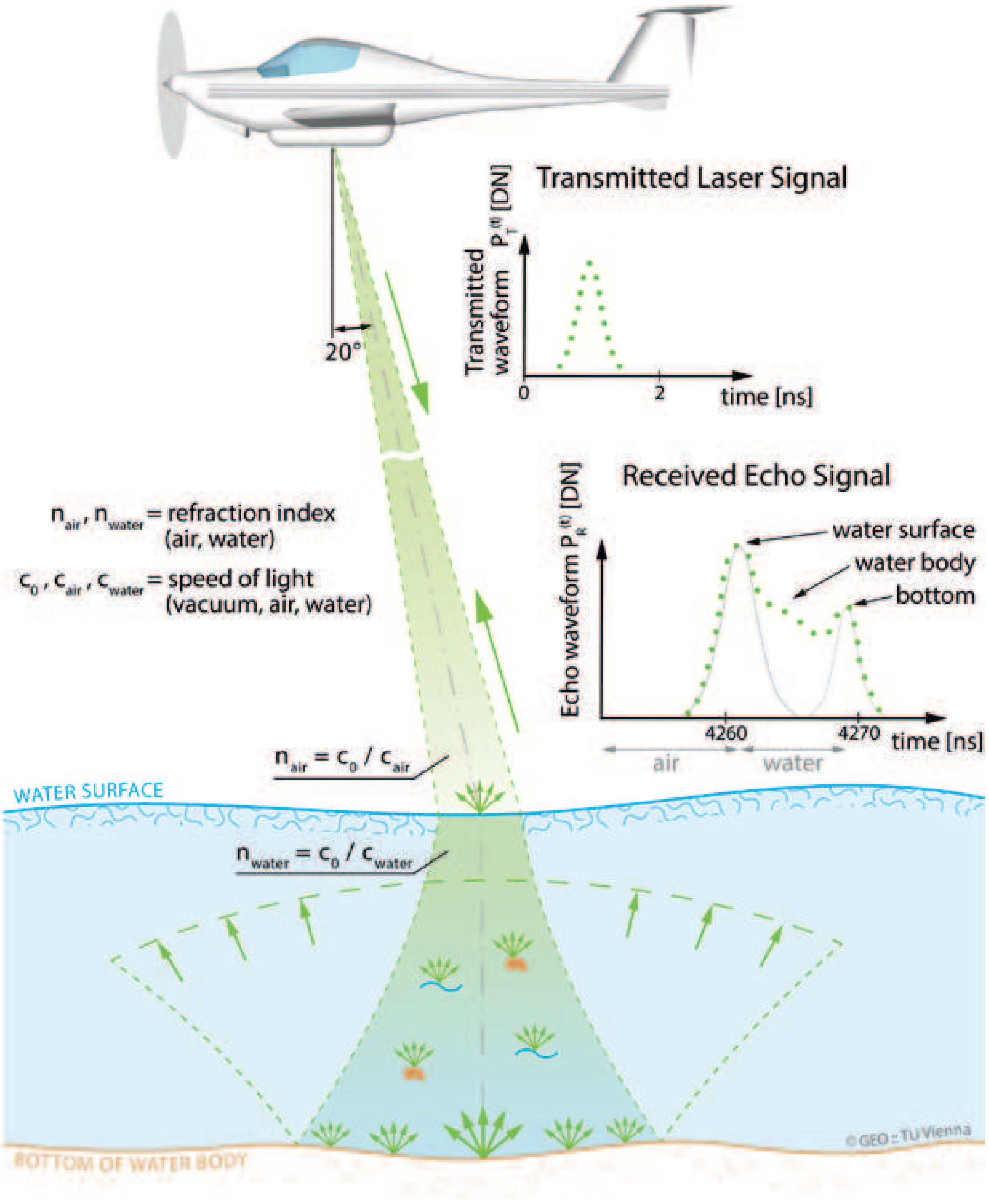

Fig. 2: Scheme explaining an ALB pulse.

It has, however, never been tested in Croatia with dense Mediterranean vegetation, which is a challenge for ALS: the vegetation is considerably low, extremely dense, and contains a considerable amount of evergreen plants.

During data acquisition, ALS systems operate in the Near or Short-Wave Infrared wavelength (typically using stable laser sources at a 1064 nm or 1550 nm wavelength), which is largely absorbed by water bodies.[16] Therefore, conventional ALS systems have a limited applicability under wet conditions and when water penetration is desired. In these cases, other wavelengths have to be utilised as laser sources. A green laser at 532 nm is very well suited for laser bathymetry from the air and is used in most ALB systems.[17]

ALB is not an entirely new technique. Its first applications (detecting submarines) go back as far as the mid-1960s, shortly after the invention of the laser.[18] Here, it is worthwhile to mention that until the turn of the millennium several operating systems were available.

Similar to ALS, a bathymetric laser scanner is usually mounted below an airplane or helicopter, where it emits short green pulses (typically 200.000) towards the earth's surface (both water and terrain). Each pulse will result in one or more echoes reflected from various objects along its path (vegetation, buildings, cars, ground surface etc.). The location of each reflecting object is calculated using the angle of the emitted laser beam, the distances to the reflecting object (measured by the time delay between emission and each received echo), and the position of the scanner (typically determined using differential global positioning system (dGPS) and an inertial measurement unit (IMU)).[19] This results in a detailed and accurate terrain model of the scanned area and works also in forested areas, where all echoes coming from vegetation have to be filtered out before a digital terrain model (DTM) is calculated.

With ALB, the process is complicated[20], because when entering the optically thicker medium of water, each green laser pulse is (1) deflected and (2) its propagation speed is reduced (Fig. 2). Deflection varies both due to the scan angle of the laser pulse and the roughness of the water surface. Therefore, the water surface has to be detected and modelled in post-processing to be able to correctly apply the refraction correction. (3) Also, the optical properties of water further spread the laser beam resulting in a weakened backscatter-echo, a more difficult echo detection, and an increased uncertainty of depth estimation (Mullen, 2009; Cochenour et al., 2008; Kunz et al., 1992). Since the maximum survey-depth mainly depends on water clarity, it is usually specified in Secchi depths. This is an empirical water clarity measure denoting the depth at which a 20-30 cm wide white disc (sometimes painted with a black and white pattern) is just perceptible.

For eye safety reasons, either the green laser beam has to be spread to a footprint diameter of several meters or the energy of the laser pulse has to be reduced. Current ALB systems use high energy pulses, which are spread over a large footprint area. This results in high underwater penetration depths between 2-3 Secchi depths. Depending on the clarity of water, this can equal a depth of 50 meters and more.[21] This rather high penetration depth is however traded off by rather wide ground sampling distances of 2-5 m at typical flying heights between 200 and 500 m.[22]

Although their spatial resolution between 2 and 5 m would be useful to visualise and investigate submerged landscapes[23], current ALB systems would not meet the criteria specified for the archaeological research in this paper. Therefore, the recently designed hydrographic laser scanner RIEGL VQ®-820-G, manufactured by the company RIEGL Laser Measurement Systems GmbH in cooperation with the University of Innsbruck Unit of Hydraulic Engineering, was tested.[24]

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[16] Curcio, Petty 1951.

[17] For example SHOALS Guenther et al. 2000a; Guenther et al. 2000b, 16; for Hawk Eye II see McNair 2010, 25.

[18] Mandlburger et al. 2011, p. 2417. For an overview of the early historical development, we refer to Guenther et al. 2000b, p. 3.

[19] Doneus et al. 2008.

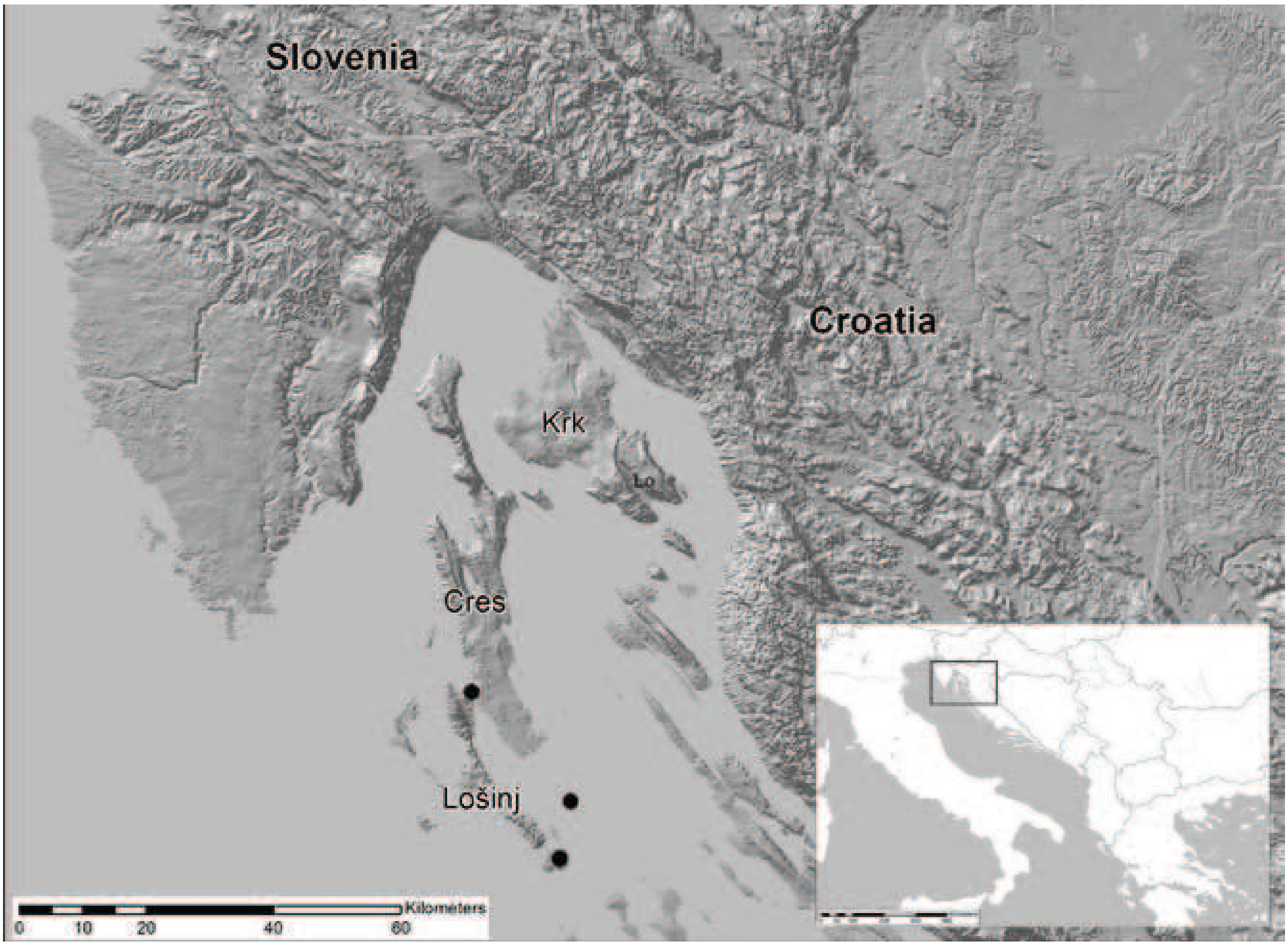
[20] For a detailed description, see Doneus et al. 2013.

[21] Guenther et al. 2000b, p. 5; Wojtanowski et al. 2008.

[22] Guenther et al. 2000b, p. 3-5.

[23] E.g. Westley et al. 2010.

[24] Riegl 2012; Doneus et al. 2013.



For eye-safety reasons, the energy of the laser pulse is reduced and the instruments beam divergence is wider compared to topographic ALS systems (0,2-0,5 mrad). This results in a footprint diameter of 0,5 m at a flying height of 500 m. Altogether, this results in a reduced water penetration capability of about 1 Secchi depth. The returning echo waveform is digitised with an interval of 1 ns and can be either processed online[25] or stored and post-processed[26]. Similar to ALS, full-waveform analysis results in additional physical parameters which can be utilised to improve the quality of the resulting DTM and enhance interpretation.[27]

To test the capabilities of the new ALB system for archaeological purposes, a flight mission was arranged at the end of March 2012 over selected case study areas. They include mainly islands of Cres and Lošinj; together with the island of Krk, they belong to the most northern group of Croatian islands.

Data acquisition

The test flight was conducted by Airborne Technologies (ABT) on 29th of March 2012 between 10:54 and 11:33 local time. Wind and water conditions were calm. The flying height was approximately 450 m above ground level, which resulted in footprints of 0.45 m diameter on the water surface. The effective measurement rate was approximately 200 kHz. To guarantee eye-safety, the low energy mode, with a special instrument setting provided by RIEGL, was used. The scan angle was set to the full field of view of the instrument (60 degree). According to Mobile Geographics (http://tides.mobilegeographics.com/calendar/year/3554.html), which utilizes the software Xtide (http://www.flaterco.com/xtide/tty.html),

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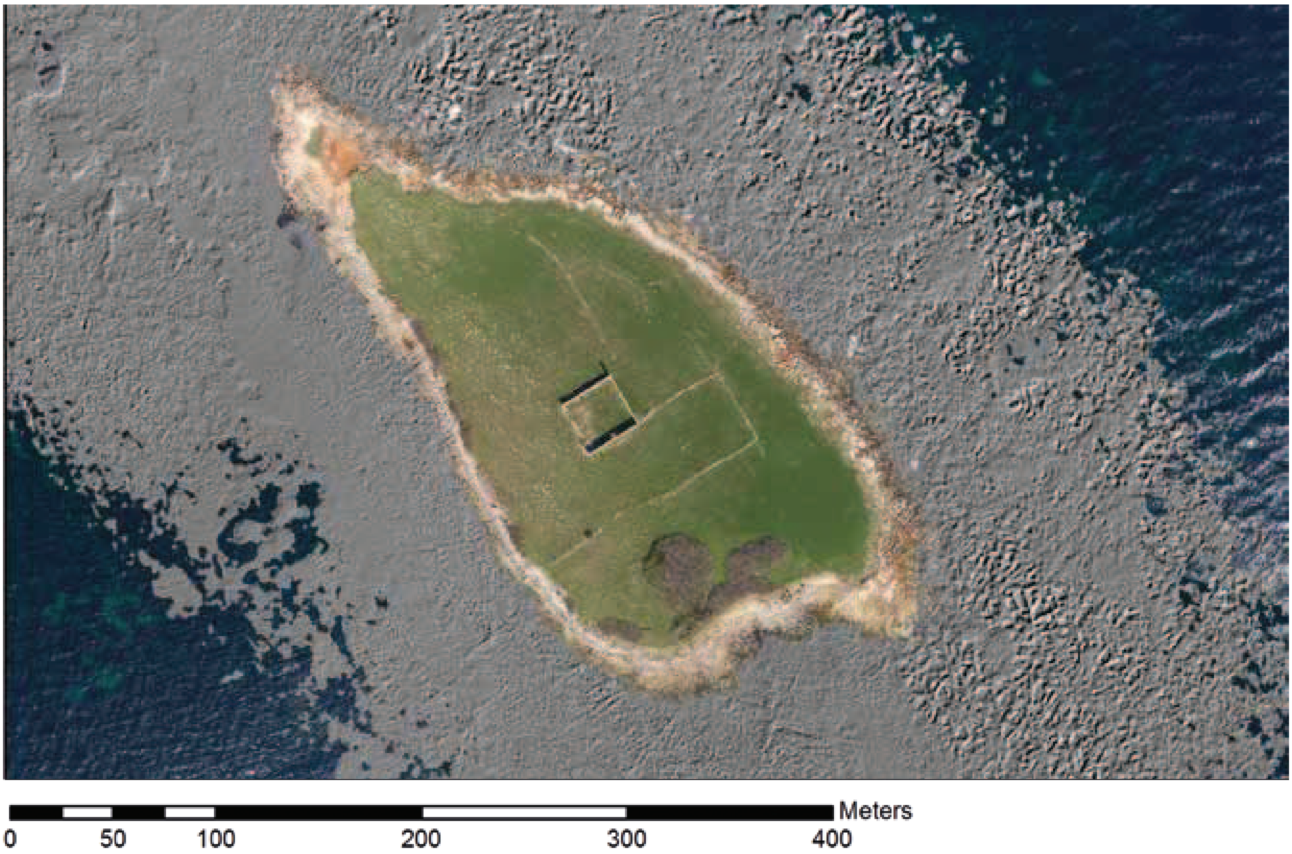
[25] Online waveform processing see Pfennigbauer, Ullrich 2009.

[26] Full-waveform processing – see Hug et al. 2004.

[27] E.g. Wang, Philpot 2007.

Fig. 4: Aerial photograph of the small island of Palacol from October 2012.

Fig. 5: Palacol. Combination of orthophotograph and ALB-derived DTM. The DTM id shaded with a light source in NW.



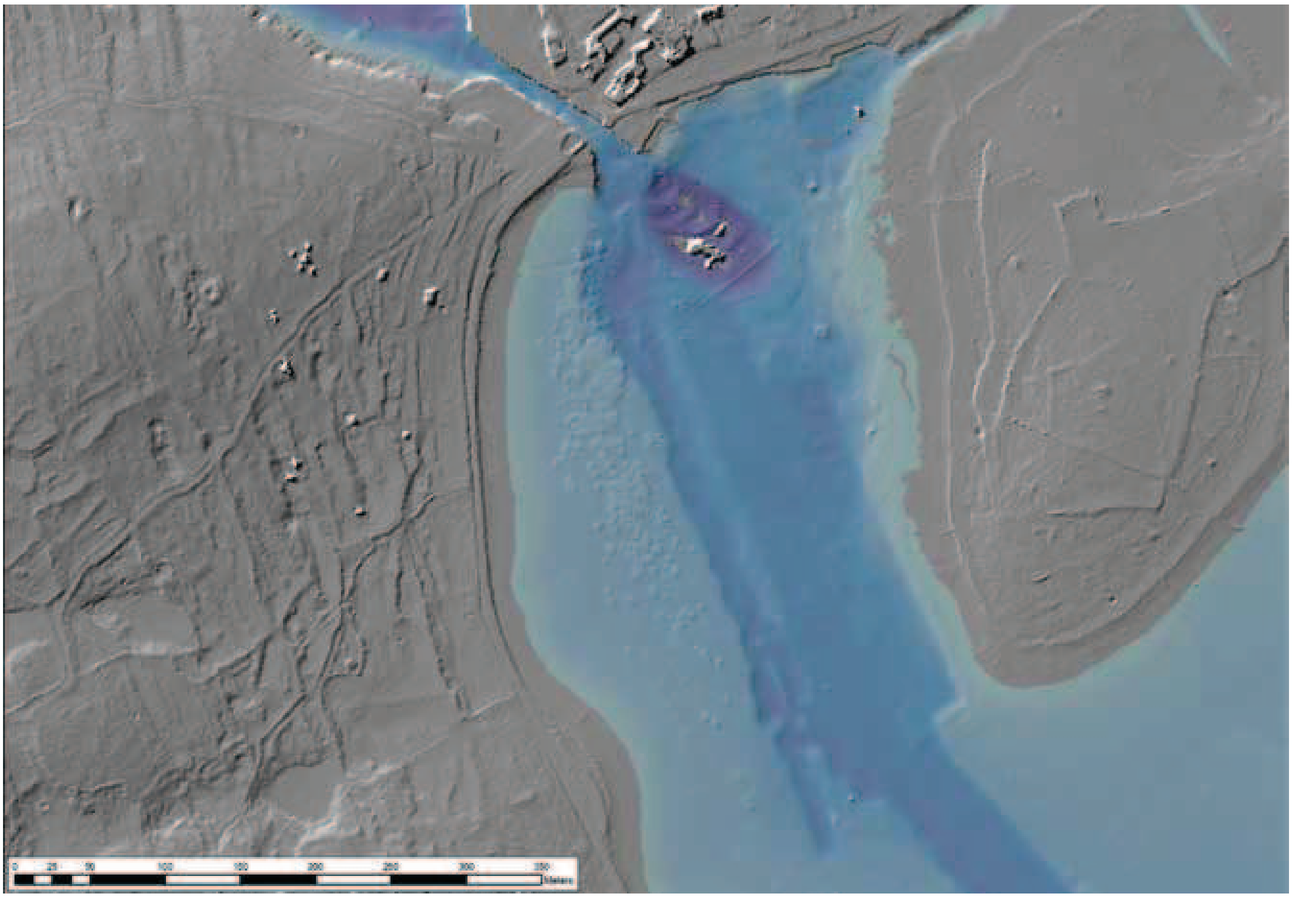


Fig. 6: ALB-derived terrain model of Osor showing the topography of both land and underwater surface (colour-coded in blue). The linear, deeper areas are dug out to maintain a navigable fairway.

low tide occurred on March, 29 at 7:49 while high tide was at 23:25. This means that the data acquisition took place at low tide conditions (the maximum tidal range is 61 cm).

The case-study areas were covered by longitudinal strips with an overlap of 70% and one or more cross-strips. Echo detection was realized using the scanners online waveform processing capability.[28] The data was processed by ABT, using the software RiPROCESS. This resulted in a total point cloud (including all echoes) with a density of 10 to 50 points per square meter.

After strip adjustment and filtering, the point cloud was imported into a GIS environment for further visualisation and interpretation. There is already abundant literature regarding archaeological visualisation of ALS-derived DTMs.[29] In this study, hillshade, slope, and local relief model[30] were calculated and used both exclusively and in various combinations.

Results

Our case study area includes mainly the islands of Cres and Lošinj, which form, together with a dozen of smaller islands, a small archipelago (Fig. 3). In the following, the results of the ALB mission will be presented using three sites: (1) the small island of Palacol, (2) Osor and (3) the Island of Sv. Petar.

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[28] See Pfennigbauer, Ullrich 2009.

[29] Bennett et al. 2012; Challis et al. 2011; Kokalj et al. 2013.

[30] Hesse 2010.

Fig. 7: Orthophotograph, which was acquired during the laser scan. The dense vegetation does not give any insight to the archaeology hidden below.

Palacol

The small island of Palacol lies few nautical miles east of the island Lošinj. A small fortress has been preserved to this day, with walls up to 4.5 m high (Fig. 4).[31] For test purposes the whole island was recorded which has resulted in the detailed documentation of the underwater topography with a point density of 6 to 12 points per m^2. From the data, a DTM with a resolution of 0.25 meter could be derived (Fig. 5). The surface model clearly shows the rugged underwater topography in detail. Although no archaeological structures could be detected in the DTM so far, it will in near future be used to simulate the sea-level at different times in the past.

Osor

The city of Osor is located at the isthmus between Cres and Lošinj. The city was founded already in the Iron Age, and has developed during the Roman and Byzantine period to one of the most important centres in eastern Adriatic. The importance of Osor is probably based on its strategic position for sea-faring. Until Roman or pre-Roman times, both islands were connected, afterwards a channel was dug at Osor separating Cres and Lošinj. The location of the city is therefore seen as important, because it was able to control the sea routes.[32] While its geographic location was the main reason for the development of the city, topography was in later times the main reason for its

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[31] Badurina 1982.

[32] Faber 1980; Faber 1982; Stražičić 1995.

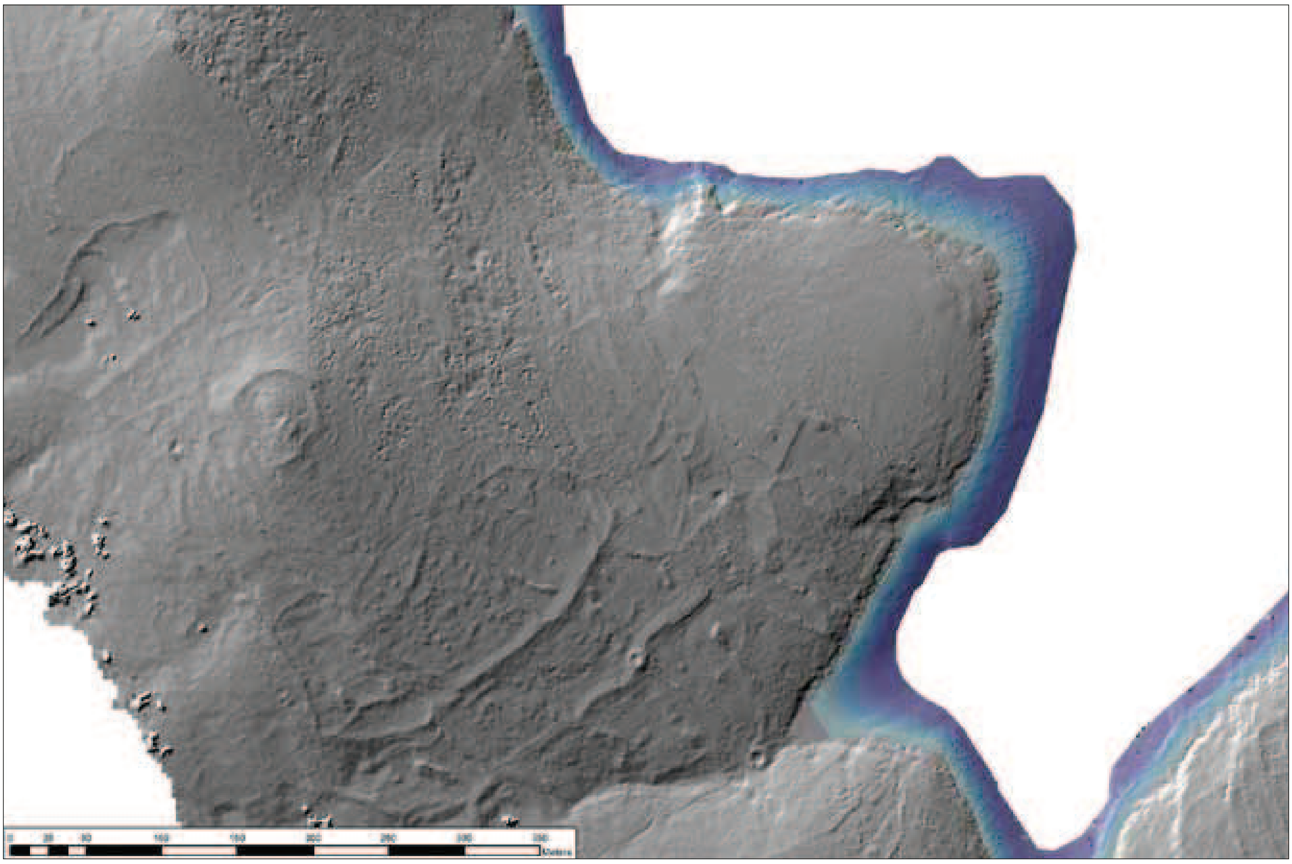

Fig. 8: ALS-derived DTM of the area depicted in Fig. 7. Despite the dense and low vegetation, enough reflections from the ground surface could be captured to enable a view of the archaeological features in relief.

decline.[33] ALB data clearly show that the water in the bay of Osor is extremely shallow, a fact which makes problems for shipping to the present day, since fine sediments continuously filled up the fairway channel. This was finally the main reason why the city was abandoned in the Middle Ages - neither the size of the channel nor the depths of the sea were suitable for the then newly developed large ships. The linear features, which are deeper areas under water and therefore depicted in dark blue in Fig. 6, are dug out areas in an attempt to oppose the silting of the bay and create a lasting and deeper fairway channel. Several attempts can be distinguished (several parallel and partly intersecting “ditches”).

Next to the topography under water the ALB-data could be used to derive digital terrain models, which are cleared of vegetation. While dense Mediterranean vegetation obscures any archaeological site on the orthophotograph (Fig. 7), the DTM (Fig. 8) clearly shows archaeological and historical landscapes containing terraces, pathways, dry stone walls, a fortified settlement, and lime kilns – parts of the man-made landscape that is still preserved under the Mediterranean vegetation. These results clearly demonstrate that using ALS/ALB in Mediterranean environments bears great archaeological potential.

Sv. Petar

The Island of Sveti Petar is located on the northern Croatian Adriatic coast, 2 kilometres southwest of the Island of Lošinj, separated from the island of Ilovik by a 200-400 m wide channel. The maximum extents of the island are roughly 2000 m by 700 m. Altogether; it occupies an area of 94 hectares. Its highest elevation is a roughly 64 meter high hill in the south. The geology is comprised largely of limestone, densely cov-

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[33] Stražičić 1995, p. 80 f.

Fig. 9: Aerial photograph from October 2012 of the southern coast of Sv. Petar showing the site of the Roman villa mentioned in the text.

ered with typical Mediterranean vegetation consisting mainly of dense, rigid, mostly evergreen shrubbery (macchia). In some areas, abandoned and recently used olive tree plantations can be found, which are enclosed by dry stone walls. Pine trees are mainly confined to the coastal areas.

Macchia, which is anthropogenic secondary vegetation, and a system of dry stone walls covering most of the island are indicators of past intensive human utilization, although the island is uninhabited today. The advantages of the natural harbour between Sv. Petar and Ilovik, which offers protection from most winds, were recognized early and the small island was already populated in prehistory.[34] More prominent sites on the island are a monastery and church of Saint Peter dating back to the 11th century, which houses the present-day cemetery of Ilovik, and a Venetian fortification from the late 16th century.[35] The focus of the test scan was, however, a large Roman settlement complex (Fig. 9). The remains are located on the southern coast of Sv. Petar, opposite to the village of Ilovik. A high quantity of ceramics, graves, and architectural details as well as widespread building material demonstrates the importance of this Roman site.[36]

The remains of Roman buildings have been located both on land and in the sea. This makes the site interesting for our research – due to the changing seawater level of the Mediterranean during the last 1.500 years large building sections have become submerged (Fig. 9). Degree and rate of the sea-level rise are still a matter of debate (suggestions range from 1,5 to 3,1 metres)[37]. Submerged archaeological remains and tidal notches

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[34] Ćus-Rukonić 1982, p. 12.

[35] Fučić 1949, p. 74 ff.

[36] Fučić 1949, p. 74; Bully, Čaušević-Bully 2012.

[37] Faivre et al. 2011, p. 132

Fig. 10: Sv. Petar - wall of a submerged Roman villa.

indicate a regionally varying sea-level at around 1,5 m below present mean sea-level during Roman times.[38] Therefore, archaeological coastal sites are at least partially located under water. As a result, at several locations spreading over a length of 300 metres, remains of walls which are continuing into the water could be identified (Fig. 10).

The results clearly demonstrate that ALB has the capability to shift the measurement border from the water-land boundary into the water. This allows for the inclusion of shallow-water zones, which can otherwise hardly be mapped in detail, into topographic documentation. This is important since, until now, archaeology lacked suitable methods to provide detailed maps of the topography of these extremely shallow underwater bodies. For a more detailed discussion of advantages and limitations of the technique we refer to a previous paper.[39]

What is however important, is to state that the penetration depth of the bathymetric laser scanner is a compromise between footprint size (narrow laser beam allowing for an increased resolving power) and high laser energy (allowing deeper water penetration) due to eye-safety reasons. In our case, a small footprint size was needed to be able to derive a detailed DTM. This of course resulted in a lesser penetration depth of around 8 m. This depth was achieved under ideal conditions, i.e. on a calm day and over clear water with a relatively smooth water surface.

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[38] Antonioli et al. 2007; Faivre et al. 2010.

[39] Doneus et al. 2013.

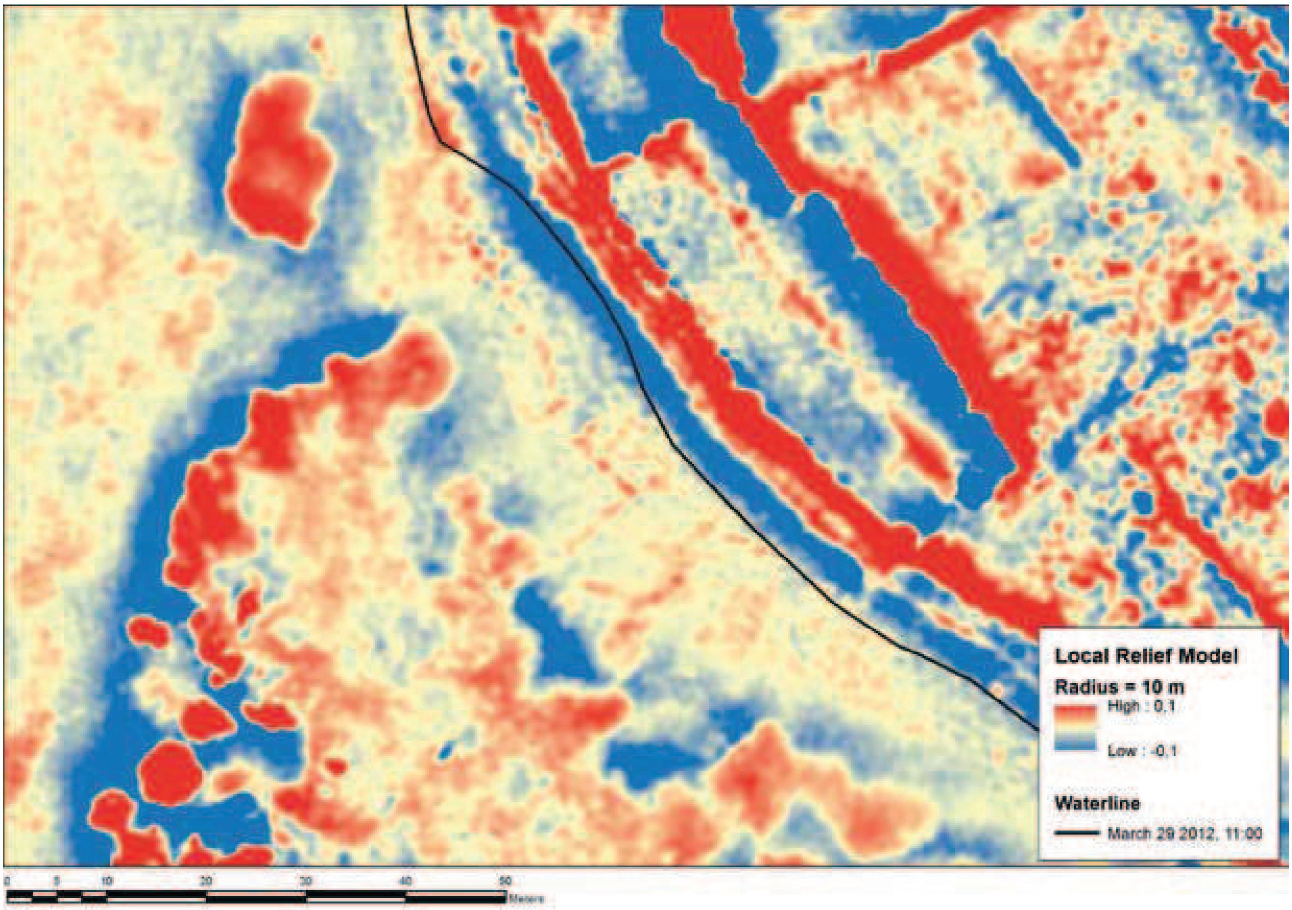

Fig. 11: The local relief model of the submerged platform reveals raised linear structures and rectangular areas (in red). Kernel-size of the low-pass filter was 10 m.

One other major advantage of ALB compared to other bathymetric methods (mainly different versions of sonar – sound navigation and ranging) is the short acquisition time needed. Within just 40 minutes, an area of 10 square kilometres was covered with a high point density in Sv. Petar.

Conclusion

The motivation behind this paper was the need for a new approach for digital documentation of archaeological landscapes in Mediterranean environments, which would allow us to document and interpret an entire coastal area combining land and under water surface. To our knowledge, no archaeological investigations using novel ALS /ALB systems has been conducted so far[40] in this kind of Mediterranean environment. The results were very encouraging and proved the viability of this technique even in these difficult environmental settings. The results can be summarized in three categories: high quality topographical mapping, topography as a key for archaeological interpretation and last but not least, documentation of archaeological heritage under water.

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Copyright for Fig. 2: Department of Geodesy and Geoinformation Research Group Photogrammetry, E120.7.

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[40] With the exception of the already published paper Doneus et al. 2013.

Acknowledgments

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ZRAČNO LASERSKO SNIMANJE (ALS) I MEDITERANSKI OKOLIŠ – ISTRAŽIVANJA U HRVATSKOJ

(Sažetak)

Arheologija Mediterana kombinira istraživanja u različitim okruženjima. Kao posljedica korištenja različitih metoda u kopnenim i podvodnim zonama, te u zonama plitke vode, pojavljuje se umjetna granica između arheološke dokumentacije na kopnu i pod vodom. Osim toga, istraživanja arheološke topografije uglavnom su ograničena na kopno i na zone plitkog mora, iako je poznavanje podvodne topografije vrlo bitno za razumijevanje organizacije i raspodjele arheoloških naseobina na otocima i obalnim područjima. Premoščivanje „granice" između kopna i mora stoga zahtijeva razvoj novih metoda arheološke dokumentacije. Najnovija tehnika koja kombinira kopnena i podvodna istraživanja je Airborne Laser Batimetrija (ALB), koja koristi zeleni laser i može stoga biti primjenjena kod dokumentacije u podvodnim područjima i u zonama plitke vode. Ovisno o čistoći mora (Secchi dubina) ovi sustavi mogu pružiti detaljnu karakterizaciju podvodne topografije i biti korišteni za prospekciju arheoloških nalazišta do dubine od 8-10 m.

Članak raspravlja mogućnosti i ograničenja ALB metode te navodi kao primjere nekoliko nalazišta na Cresu i Lošinju na sjevernom Jadranu. Podmorska arheološka prospekcija koja je testirana na ovom području, pokazala je visoku kvalitetu topografskih karata na kopnu i u moru. One služe digitalnoj dokumentaciji arheološke baštine kao i kasnijim istraživanjima vezanim za organizaciju naseobina, luka, plovnih puteva, i slično.

Ključne riječi: zračno lasersko snimanje, zračna laserska batimetrija, arheološka prospekcija, podmorje, podvodno nalazište, rimska vila, Sredozemlje, sjeverni Jadran

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