Analysis of State-of-the-Art Hydrographic Survey Technologies

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Key words: „Hydrography", „Airborne/Spaceborne techniques", „In situ techniques"

SUMMARY

Bathymetry data is critical for safety of navigation and is used for many other applications. The world's oceans cover 71% of the Earth, but we still have mapped less than 20 % of the world's oceans and 50 % of the total global continental shelf area (shelf depth is shallower than 200 m) was unsurveyed or inadequate surveyed according to IHO S-44 standards. Continental shelves make up about 8% of the entire area covered by oceans and seas and the remaining parts have a poorly defined sea bottom. Therefore, it is necessary to find efficient and preferably coast effective methods of bathymetry determination.

Determination bathymetry or measurement of underwater topography is very challenging and demanding task. Therefore efforts are being made to find new techniques which will successfully solve this task, besides performing traditional survey by using big and expensive hydrographic research vessels. The decision goes in two directions solving: airborne/spaceborne and in situ measurement techniques.

Today three types of airborne/spaceborne shallow waters bathymetric measurement techniques are most commonly used: LiDAR or laser scanner technique, Satellite Derived Bathymetry technique (multispectral imagery) or its sub-variant Airborne Derived Bathymetry (ADB), and SAR technique (Synthetic aperture radar - SAR imagery).

There are also two in situ techniques which have started to be used in the last few years: Unmanned autonomous vehicle (UAV) and Underwater drone or Remotely Operated Vehicles (ROV).

The paper briefly describes each of these "non-traditional" data collection techniques as new and innovative technologies that can increase the efficiency of collecting bathymetric data. The description include all advantages and disadvantages of individual techniques, the achieved measurements accuracy and ranges of the sea depths. Finally, it was concluded that SDB and LiDAR methods are suitable for bathymetric survey of shallow coastal areas, SAR method is used to determine the offshore depth ranging between about 10 and 100 m, while ASVs, USVs, AUVs, and UUVs are appropriate for a variety of offshore and coastal hydrographic surveys.

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1. INTRODUCTION

Determination bathymetry or measurement of underwater topography is very challenging and demanding task. Sea depth data was by far the most expensive spatial data. Systematic bathymetric survey with satisfactory data accuracy, according to International Hydrographic Organization (IHO, 2008) Standards for hydrographic surveys S-44, was recorded only near the coast or depth area up to 200 meters (continental shelf). Many national and international initiatives have tried to present proposal to find methods and techniques to prevail this discouraged reality (e.g. GEBCO Seabed 2030 Project, https://seabed2030.gebco.net/).

Taking into considerations up today standard hydrographic methods and techniques of survey, many scientists and hydrographers proposed a few recommendations to fulfill ambitious challenges of mapping the entire oceans and seas.

There are two general directions to address this problem today: the first are airborne or spaceborne methods or measurement techniques and others are in situ techniques.

1. Today three types of airborne or spaceborne shallow waters bathymetric measurement techniques are most commonly used:
    - 1.1. LiDAR or laser scanner technique;
    - 1.2. Satellite Derived Bathymetry (SDB) technique (multispectral imagery);
        - 1.2.1. Airborne Derived Bathymetry (ADB);
    - 1.3. SAR technique (Synthetic Aperture Radar - SAR imagery).
2. There are also two in situ techniques which have started to be used in the last few years:
    - 2.1. Unmanned autonomous vehicle (UAV);
    - 2.2. Underwater drone or Remotely Operated Vehicles (ROV).

The paper briefly describes each of these “non-traditional” bathymetric data collection techniques as new and innovative technologies that can increase the efficiency of hydrographic survey. The description include all advantages and disadvantages of individual techniques, range of bathymetric measurements, the achieved measurements accuracy, and approximate cost of measurements. Finally, optimal techniques of bathymetric survey for the coastal shallow part and open sea areas have been recommended.

2. AIRBORNE OR SPACEBORNE MEASUREMENT TECHNIQUE

The basic and common feature of these techniques (methods) is that they use electromagnetic waves for measurements (Figure 1). The first two measured techniques (LiDAR and SDB or ADB) use a combination of two waves (most commonly a combination of shortwave visible and shortwave infrared), one that penetrates well into the water column and the other that reflects off the water surface. By measuring the difference between the two returning waves, we can measure the depth of the sea. The Synthetic aperture radar (SAR) technique uses long-wave electromagnetic waves or radio waves to measure the depth of the sea.

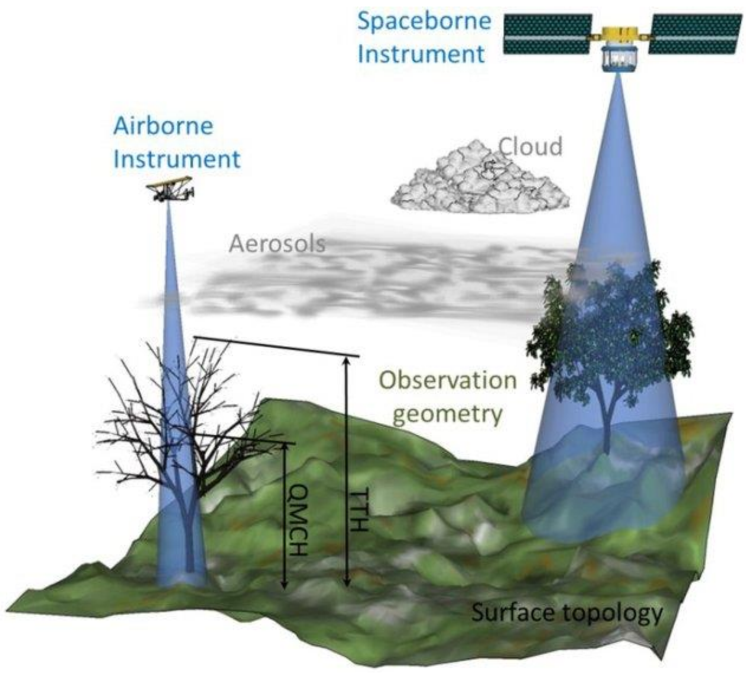

Figure 1: Airborne or spaceborne measurements technique methods (according Shang & Chazette, 2015).

2.1 LiDAR or laser scanner technique

LiDAR (Light Detection and Ranging) is a remote sensing method used to examine the surface of the Earth. An instrument the most consists of a laser, a scanner, and a GPS receiver, and it uses a light in the form of a pulsed laser to measure variable distances to the Earth (NOAA, 2020).

There are three main types of LiDAR platforms (Humboldt State University, 2016):

1. Ground based;
2. Airborne:
   a. Aerial laser scanning (ALS),
   b. Drone laser scanning (DLS),
3. Satellite.

Ground based or terrestrial LiDAR systems are on a stationary tripod or on a moving vehicle, and they are used to create highly accurate models and measurements of buildings, archeology sites, and rock formations (Humboldt State University, 2016). Airborne LiDAR platforms include systems mounted on airplanes and helicopters – ALS, and on unmanned aerial vehicles – DLS. ALS have limitations including flight altitude and scan angle that prevent the scanner from collecting a complete survey. On the other hand DLS offer ways to scan with many potential advantages over ALS. The primary advantages stem from the greater point density resulting from the lower flight altitude, which allows more precise measures of the Earth. The point density of DLS also captures the details of features in the environment, which are important for physical measures of spatial complexity (Resop et al., 2019). Satellite platforms are mounted on satellites that orbit the Earth, and they tend to cover large areas with less details (Humboldt State University, 2016).

LiDAR has a wide range of applications. Firstly it can be used in any situation where we need to know the structure and shape of Earth's surface. Furthermore, it is often used for land management and planning efforts, including agriculture, forestry, geologic mapping, hazard assessment (floods, landslides, lava flows, and tsunamis), and river and watershed surveys (AGI, 2020). Its high resolution give it applications in archeology, law enforcement, medicine, meteorology, military, mining, visualisations and gaming, and much more (Thomson, 2019).

There are two types of LiDAR (Leatherman, 2003):

1. Topographic;
2. Bathymetric.

Topographic LiDAR uses a near-infrared laser beam to map the land. On the other hand bathymetric LiDAR uses infrared and green laser beam (Leatherman, 2003). Bathymetric LiDAR sensors are the GPS receiver, the inertial measurement unit (IMU), the laser scanner and the sensor. The GPS receiver gives the aircraft position, the IMU gives the roll, pitch and yaw of the aircraft, the laser scanner emits the signal in a particular pattern, and the sensor reads the returning signal. A green laser beam is transmitted to the water surface where a portion of the energy is returned to the GPS receiver, while the remainder continues to the bottom and is subsequently reflected back to the receiver (Quadros, 2016). Bathymetric LiDAR uses two wavelengths, because the water floor needs to be measured separately from the water surface as it is shown in Figure 2. An infrared laser beam with a wavelength of 1064 nm quickly absorbed and it is used to detect the water surface. A green laser beam with a wavelength of 532 nm penetrates in the water in order to measure water depth. The return infrared signal gives the height of the plane above the water, and the water depth is calculated from the difference between the two return signals (Quadros et al., 2008). Bathymetric LiDAR is used in the hydrographic survey to capture geospatial data of the coastline and shallow waters, and in the river survey it can measure aspects of river data such as depth, length, and flow. Its advantages are more obvious in areas inaccessible to surveying vessels (Zhang et al., 2019).

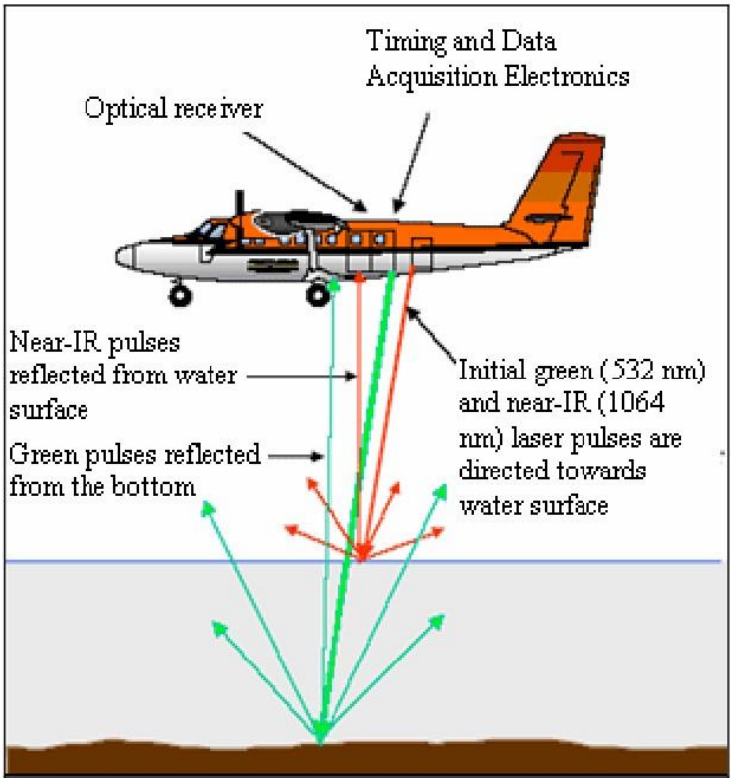

Figure 2: Bathymetric LiDAR System (LaRocque and West, 1990).

2.2 Satellite Derived Bathymetry technique

Satellite Derived Bathymetry technique (SDB) is relatively new survey remote sensing acquisition technique method, which uses high-resolution multispectral satellite imagery or other remote multispectral imagery for nearshore or shallow water depth determination (UKHO, 2015). Method has been recently considered as a new promising technology in the hydrographic surveying industry, especially due to the rapid development of satellite techniques. SDB is a survey method founded on analytical modeling of visible and infrared bands water column penetration. Today, SDB data has potential to become most important low cost source of spatial data especially hydrographic data. Satellite-derived bathymetry procedure provides a simple reconnaissance tool for hydrographic offices and all other kinds of spatial experts. The procedure is already in commercial use and its steps are documented in public literature (Pe'eri et al., 2013). The satellite imagery provides repeatable coverage of remote areas.
Depth estimation from satellite images is based on the theory that light is attenuated exponentially in the water. The procedure (workflow) to obtain bathymetric data from satellite imagery includes the following basic steps, according to Gao (2009):

1. Pre-processing;
2. SDB Depth Calculation:
    a. Water separation,
    b. Spatial image filtering,
    c. Glint/cloud correction,

d. Bathymetry algorithm application,
e. Vertical referencing or Tidal Correction,

3. Post processing (QA/QC).

The result of satellite derived bathymetry (SDB) method for the acquisition of bathymetric data in the Adriatic Sea (area of Hramina Bay), which used free of charge Landsat 8 image on 14 February 2017 and Sentinel 2 image taken on 09 May 2017 is shown in Figure 3.

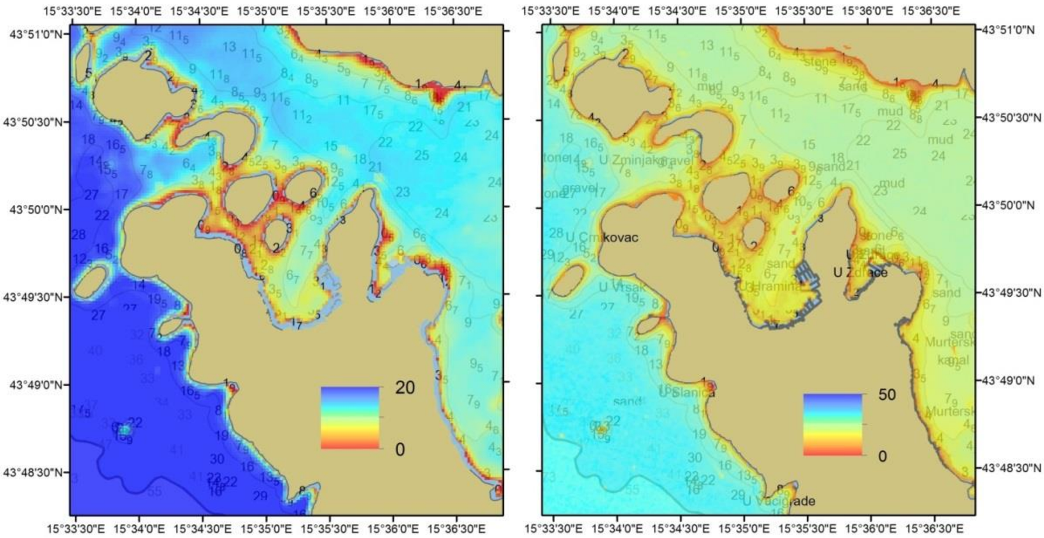

Figure 3: Satellite-derived water depth of Hramina Bay obtained from Landsat 8 (left) and Sentinel 2 (right) (Leder and Duplančić Leder, 2017).

It can be concluded that generally depth gradients and coastline are very well surveyed by using SDB method, while individual shoals are not detected because of low spatial resolution of the SDB method (Leder and Duplančić Leder, 2017).

2.3. Airborne Derived Bathymetry

With Sentinel imaginary authors have obtained good results, but were not satisfied with the resolution, and therefore decided to apply SDB technology on UAV platform. Bathymetry modelling method according Stumpf model (Stumpf et al., 2003) or application of SDB on another platform, could be called Airborne Derived Bathymetry (ADB). The specificity of this method is (Aarnink, 2017; Zinke and Flener, 2013):

- Low cost and wide availability of technology;
- Pre-processing procedure of control targets points (GCP) establishment and camera with RGB and IR band calibration (Zinke and Flener (2013) used Canon EOS 550 D + 18-55 IS lens on Microdrone MD4-1000 platform);
- Geo-referencing of image mosaics based on measured ground control targets points (GCP);
- Bathymetric modelling (e.g. Stumpf method).

Advantages of ADB as opposed to SDB:

- Maneuverability, portability, and safety method;
- Low cost;
- Ease of operation.

Disadvantages of ADB as opposed to SDB:

- Short flight autonomy;
- Long term pre-processing procedure.

2.4 Synthetic aperture radar (SAR) technique

Synthetic aperture radar (SAR) is an active instrument which yields high-resolution images in the microwave frequency band. The radar works by transmitting electromagnetic waves and then collecting, digitizing, and storing their echoes for later processing. Radar microwaves cannot penetrate into the water body, SAR can retrieve information on underwater bottom topography (or bathymetry) indirectly by measuring variations in the small-scale sea surface roughness. This method is used for capturing the offshore water depth ranging between about 10 and 100 m. SAR (TerraSAR-X images, ESA Sentinel-1 data) works by detecting the changes in the wavelengths in the deep waters.

The backscatter data detected by SAR depends on the roughness of the sea surface and the length scale of the roughness. There are two methods of bathymetry derivation from SAR satellite data: first one determines water depth directly from the measurement of the ocean swell peak wavelength and wave direction and the other one of sea surface gravity waves. Measured values are processed using a fast Fourier transformation (FFT) and the linear wave dispersion relationship. Detail description of bathymetry retrieval from SAR images can be find in Wiehle et al., 2019).

3. UNMANNED VEHICLE SYSTEMS IN HYDROGRAPHIC SURVEY

In this section "in situ" unmanned vehicle systems (UVSs) will be described. There is many performance of unmanned vehicle systems (UVSs). The movement or navigation of these systems may operate with various degrees of autonomy: either under remote control by a human operator, or fully or intermittently autonomously, by on-board computers. In general three "in situ" systems are used in hydrographic survey as following:

1. Autonomous Surface Vehicles (ASVs) and Unmanned Surface Vehicles (USVs) are vehicles that operate on the surface of the water (watercraft) without a crew (Romano and Duranti, 2012);
2. Autonomous Underwater Vehicles (AUVs) and Unmanned Underwater Vehicles (UUVs) are robotic vehicles designed to travel underwater without the need of direct human operators (Danson, 2002);
3. Remotely operated underwater vehicle (ROV) is a tethered underwater mobile device.

Each of these types of vehicles on board may have equipment for, systems for platform stabilization, and equipment for hydrographic survey (single beam and multi beam echo sounders). Many hydrographic offices increasingly have used such vehicles for hydrographic survey in recent years and there are efficient and inexpensive version of equipment for hydrographic and bathymetry survey. For example, with the use of unmanned systems, NOAA is reducing operational costs and manpower requirements (https://oceanservice.noaa.gov/podcast/oct18/nop19-unmanned-systems.html).

3.1 Autonomous and Unmanned Surface Vehicles

Modern autonomous and unmanned vessel (Autonomous Surface Vehicle – ASV, Unmanned Surface Vehicle – USV) was first designed in 1993 and was designed for various missions: science, bathymetric mapping, defense, and general robotics science (Manley, 2008).

Today USVs have been developed by many corporations and academic labs. There is a variety of design solutions in the construction of the hull and boat propulsion (Manley, 2008) as well as communications and system operations.
It is important to emphasize that the UK Ship Register has signed on 13 November 2017 its first ever unmanned vessel (ASV's C-Worker 7) to the flag, showing how it is adapting to the changes of the maritime industry (https://www.ukshipregister.co.uk/news/uk-ship-register-signs-its-first-unmanned-vessel/).

In this paper the only one USV (designed by the Teledyne Marine company) will be described with regards to their importance for the use of unmanned boats in hydrography.
The Teledyne Oceanscience Z-Boat 1800RP with new ruggedized design and interchangeable sensor well, offers an entirely new option for high-resolution shallow-water hydrographic surveying (Figure 4). Get multibeam bathymetry data where conventional methods are not feasible or safe, and avoid mobilizing a workboat or vessel of opportunity. The Z-Boat

1800RP uses advanced radio telemetry to offer remotely-operated hydrographic surveys. All data is accessible in real time, giving the operator total control over the survey process. Z-Boat navigation is easy using the GNSS position and heading available onboard, and remotely viewed at the operator location (http://www.teledynemarine.com/z-boat-1800rp).

Figure 4: Unmanned surface vessel Teledyne Oceanscience Z-Boat 1800RP
http://www.teledynemarine.com/z-boat-1800rp

3.2 Autonomous and Unmanned Underwater Vehicles

Autonomous and Unmanned Underwater Vehicles (AUVs and UUVs) are robotic vehicles designed to travel underwater without the need of direct human operators. They can be equipped with different kinds of payloads such as (side scan) sonar, bottom profilers, cameras, and multibeam echo sounders. Their highly versatile configuration possibilities in combination with independent movement make AUVs a powerful instrument in any underwater surveying or inspection job (https://geo-matching.com/auvs-autonomous-underwater-vehicles).

The Kongsberg Maritime HUGIN Superior AUV System (Figure 5) is one the most capable commercially available AUV (https://www.kongsberg.com/maritime/products/marine-robotics/autonomous-underwater-vehicles/AUV-hugin-superior/). It offers the best data quality and coverage coupled with the most accurate navigation and positioning solution there is. Packaged as a complete system, HUGIN Superior carries more sensors than ever before over greater distances enhancing productivity and cost effectiveness. For hydrographic point of view it is high-resolution high-speed seabed mapping system with multibeam, sub-bottom profiler, and magnetometer instruments designed for the application up to the 6000 m depth. Due to the relatively large dimensions, it is necessary to use a research vessel to operate the HUGIN system (Figure 5).

Figure 5: Autonomous Underwater Vehicle HUGIN produced by the Kongsberg Maritime. https://www.kongsberg.com/maritime/products/marine-robotics/autonomous-underwater-vehicles/AUV-hugin-superior/

3.3 Remotely operated underwater vehicle (ROV)

A remotely operated underwater vehicle (ROV) is a tethered underwater mobile device (Figure 6). ROVs are unoccupied, highly maneuverable, and operated by a crew aboard a vessel. ROVs are unoccupied underwater robots, connected to an operator via a series of cables. The connecting cables transmit command and control signals to and from the underwater vehicle and the operator, allowing remote navigation of the vehicle.

A typical hydrographic ROV configuration includes a video camera, lights, sonar systems, and an articulating arm. The articulating arm can be used for retrieving small objects, cutting lines, or attaching lifting hooks to larger objects. The ROV system includes the vehicle, deck unit, tether management system, hand box controller, laptop computer, and video display (https://en.wikipedia.org/wiki/Remotely_operated_underwater_vehicle).

Current hydrographic uses for the ROV include object identification (such as submerged navigation hazards), vessel hull inspections, and least depth determination. The system is not intended to be a replacement for hydrographic diver investigations, but could serve as a substitute when diver safety is in question, or when divers are otherwise not available (https://www.controleng.com/single-article/are-rovs-more-like-robots-or-drones/).

In Figure 6 the Teledyne observation and inspection class ROV is shown. It provides state-of-the-art solution with wide variety of sensors, cameras and payloads, providing multi-mission functionality (https://www.unmannedsystemstechnology.com/company/teledyne-marine/#1).

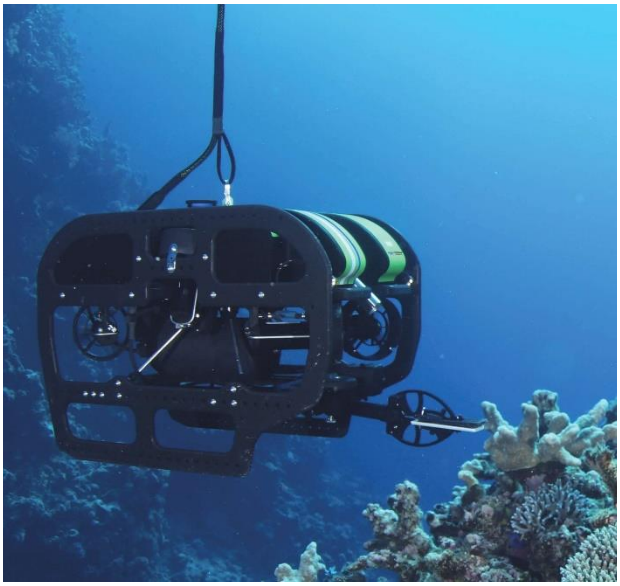

Figure 6. Teledyne-Marine ROV providing multi-mission functionality. https://www.unmannedsystemstechnology.com/company/teledyne-marine/#1

4. CONCLUSIONS

The paper presented and summarized new techniques and methods used for hydrographic survey (excluding the traditional survey by using big and expensive hydrographic research vessels), as well as their comparative advantages and disadvantages. Results are compared with traditional survey and International Hydrographic Organization (IHO) Standards for Hydrographic Surveys S-44 (IHO, 2008).

Satellite Derived Bathymetry (SDB) and LiDAR methods are suitable for bathymetric survey of shallow coastal areas with clear water (approximately to the depth of 2 secchi disc depth). It should be pointed out that accuracy of these methods does not meet current IHO Standards for Hydrographic Surveys. Therefore, these techniques are an ideal tool for the determination of bathymetric data in the marine (rivers, lakes) areas without bathymetric data or in the areas with old bathymetric data.

Synthetic aperture radar (SAR) method is used to determine the offshore depth ranging between about 10 and 100 m, and it meet IHO standards in deeper waters.

Hydrographic survey performed using modern autonomous and unmanned surface vessels (ASVs, USVs) are suitable for a variety of offshore and coastal hydrographic surveys. In coastal area it is possible to perform a survey relatively autonomous (communication is between people on the coast and the vessel), while during the offshore survey USV is working simultaneously with a research vessel. USVs can integrate a large number of different research equipment (multi beam echo sounder, side scan sonar, etc.) and the measurement results may be consistent with IHO Standards for Hydrographic Surveys.

Autonomous and unmanned underwater vehicles (AUVs and UUVs) are a powerful instruments in any underwater surveying or inspection job. They can be equipped with different kinds of modern hydrographic instruments, operating at all depths. This type of instruments are most commonly used on large research vessels (due to its dimensions), which is a drawback, but if AUV and UUV work in parallel mode with a research vessel, that drawback can be ignored. This type of measurement can reach the highest IHO Standards for Hydrographic Surveys at all depths.

A remotely operated underwater vehicle (ROV) operated by a crew aboard a vessel are currently being used in hydrography for object identification (such as submerged navigation hazards), vessel hull inspections, and least depth determination.

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BIOGRAPHICAL NOTES

Nenad Leder, born in Komiža (Vis island, Croatia) in 1958, graduated in 1981 at the Faculty of Science of the University of Zagreb, Department of Physics. His professional career as

oceanographer and hydrographer spans some 35 years at the Hydrographic Institute of the Republic of Croatia. Between 2004 and 2014 he took up the post of Assistant Director and between 2014 and 2017 he was the Director. As National Hydrographer he was Croatian government's representative at the International Hydrographic Organization (IHO) in Monaco.
In October 2004 he earned his doctor's degree with the dissertation entitled "Barotropic and Baroclinic Waves in Wider Area of Lastovo Channel". In the period between 2005 and 2009 he performed the duties of project manager in CRONO HIP Project (Croatian-Norwegian Hydrographic Information Project), through which the Hydrographic Institute of the Republic of Croatia significantly modernized its "production line" from the hydrographic survey by modern multibeam echosounder, and implementation of sophisticated database of hydrographic, nautical and oceanographic data, to the production of electronic navigational charts (ENC) and paper navigational charts from the same database.
From 2017 to the present he is an assistant professor at the Faculty of Maritime Studies of the University of Split.

Tea Duplančić Leder, born in Split in 1960, graduated at the Faculty of Geodesy the University of Zagreb. She completed her internship in 1986 at Elektrodalmacija Split, and then worked at the high school for a half year. She worked at the Hydrographic Institute from 1988 to 2007 in various positions. In 2002, she completed a specialized course at the International Maritime Academy (IMA) in Trieste for the production and maintenance of Electronic Navigation Charts, and in 2005 she attended specialist training at C-map Italy for quality control and validation of ENC data. She received her PhD in 2006 from the Faculty of Geodesy, University of Zagreb, entitled "*New Approach to the Making of Electronic Navigation Charts in Croatia*".
Since 2007, she has been employed at the Faculty of Civil Engineering and Architecture in Split, and in 2010 she was elected Vice-Dean for the study of Geodesy and Geoinformatics at the same Faculty. She performed the function until 2016.

Samanta Bačić, born in Zadar in 1993, graduated in 2017 at the Faculty of Geodesy, University of Zagreb. During her master's study in academic year 2016/2017 she was receiving a scholarship from the University of Zagreb for excellence students. The same year she got the University Award for Group Scientific Research and Faculty Award for Excellence. She has started her Ph. D. studies in November 2018 at the Faculty of Geodesy, University of Zagreb. Her research interest fall within the geodetic scientific field of applied marine, satellite and physical geodesy. She worked as professional associate in geodesy at the Department of Photogrammetry in Zagreb from February 2018 to March 2018. From April 2018 to June 2019 she had been employed as Teaching Assistant, but on the replacement, at the Faculty of Civil Engineering and Architecture of the University of Split. From October 2019 to the present she is Teaching and Research Assistant at the Faculty of Civil Engineering and Architecture of the University of Split.

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