Development of a High-Resolution Underwater Gravity Measurement System Installed on an Autonomous Underwater Vehicle

Masanao Shinohara, *Member, IEEE*, Toshihiko Kanazawa, Hiromi Fujimoto, Takemi Ishihara, Tomoaki Yamada, Akito Araya, Satoshi Tsukioka, Shinobu Omika, Tsuyoshi Yoshiume, Masashi Mochizuki, *Member, IEEE*, Kenji Uehira, and Kokichi Iizasa

***Abstract*— Recently, hydrothermal deposits below the seafloor are believed to be useful for human activity. Because the size of each deposit is much smaller than that of an offshore oil field, detailed exploration for the position and the estimated mass is needed. An underwater gravity survey just above seafloor can directly give localized mass distribution below the seafloor. Therefore, we have developed an underwater gravity measurement system onboard an autonomous underwater vehicle (AUV), which is suitable for wide area surveys close to the seafloor with high resolution. An improved gravimeter was mounted on a levelling platform and the system was contained in a spherical pressure vessel with a diameter of 50 cm. The gravimeter system was installed on a large AUV. All the power is supplied from the AUV and an acoustic communication system enables control and monitoring during observation. The first observation was carried out in September 2012 in Sagami Bay, Japan. The AUV was navigated at a constant speed and constant depth on the same profile. As a result, our system has a repeatability of 0.1 mGal. The developed underwater gravimeter has been used for mapping of gravity anomalies in seafloor deposits areas around Japan since 2013.**

***Index Terms*— Autonomous underwater vehicle (AUV), gravimeter levelling system, high-resolution underwater gravimeter, hydrothermal deposits, marine gravity measurement.**

I. Introduction

IT IS known that there are mineral deposits below the seafloor. To explore seafloor deposits, a gravity survey is one useful method. A gravity survey on the sea surface is effective for large-scale undersea resources such as an oil field. On the other hand, seafloor mineral deposits generally have much smaller scale than oil fields. A gravity survey just above the seafloor for high resolution is indispensable for exploring seafloor deposits, since gravitational force varies in inverse proportion to the square of the distance. Due to the large cost of seafloor surveys, a system which can quickly explore for seafloor deposits over wide areas with high resolution is needed. Data from gravimeters taken on ships do not have enough resolution for surveys of seafloor deposits [1]. Although ocean bottom gravimeters (OBGs), which are designed to observe in a stationary environment, have enough resolution, it is difficult to make observations at many points in a short time [2]–[4]. A survey of hydrothermal deposits below the seafloor needs higher resolution than a surface survey and requires a larger survey area than an OBG survey [5]–[7]. A gravimeter installed on an underwater vehicle satisfies these conditions. Recently, remotely operated vehicles and autonomous underwater vehicles (AUVs) have made technological progress [8]. Therefore, we have developed a gravity measurement system mounted on an underwater vehicle.

Before starting development, we estimated the required resolution necessary to detect gravity signatures associated with high-density seafloor deposits. We assumed a seafloor hydrothermal deposit of a diamond shape, 400 m in length, and 20 m thick at center, with a density difference of 1000 $kg{\cdot}m^{-3}$. These values are estimated from actual seafloor deposits around Japan. From the results of numerical experiments, we found that a gravity measurement 50 m above the seafloor needs 0.1 mGal of resolution (Fig. 1). A single AUV dive can cover a survey area of more than 1 km^2 with a high spatial density of track lines due to its speed in water. In addition, it is likely not difficult to navigate an AUV 50 m above the seafloor. For these reasons, we adopted an AUV as the platform for our underwater gravity measurement system. In addition to gravity measurement, measurement of the gradient of gravity [9] is useful to estimate seafloor deposits. Therefore, we also started the development of an underwater gradiometer mounted in an AUV, which has previously been reported [10]. In this letter, we discuss our developed submersible gravity measurement system on underwater vehicles, and the practical evaluation of our gravimeter system using an AUV in the sea.

Manuscript received January 20, 2018; revised May 10, 2018 and July 31, 2018; accepted July 31, 2018. Date of publication September 19, 2018; date of current version December 5, 2018. This work was supported by the Ministry of Education, Culture, Sports, Science and Technology, Japan under the Program for the Development of Fundamental Tools for the Utilization of Marine Resources. *(Corresponding author: Masanao Shinohara.)*

M. Shinohara, T. Ishihara, T. Yamada, and A. Araya are with the Earthquake Research Institute, The University of Tokyo, Tokyo 113-0032, Japan (e-mail:mshino@eri.u-tokyo.ac.jp).

T. Kanazawa is with the Association for the Development of Earthquake Prediction, Tokyo 101-0064, Japan.

H. Fujimoto is with Tohoku University, Sendai 980-8578, Japan.

S. Tsukioka, S. Omika, and T. Yoshiume are with the Japan Agency for Marine-Earth Science and Technology, Yokosuka 237-0061, Japan.

M. Mochizuki and K. Uehira are with the National Research Institute for Earth Science and Disaster Resilience, Tsukuba 305-0006, Japan.

K. Iizasa is with the Institute of Industrial Science, The University of Tokyo, Tokyo 153-0041, Japan.

Digital Object Identifier 10.1109/LGRS.2018.2863261

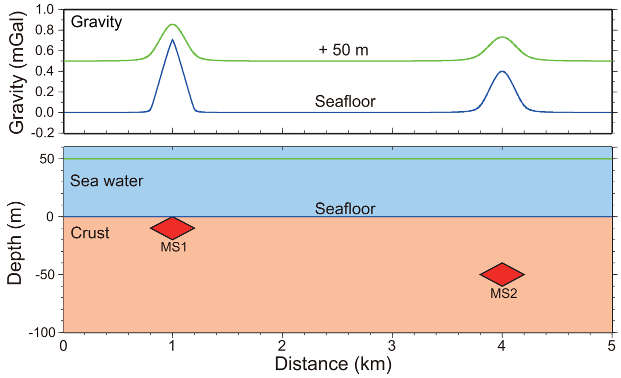

Fig. 1. (Top) Estimated gravity variation from (Bottom) model. The model has two same shape deposits, MS1 and MS2, which have density differences of 1000 kg·m^{-3} against the background. A diameter of the deposit is 400 m, and maximum thickness is 20 m. Depths of MS1 and MS2 from the seafloor are 10 and 50 m, respectively. Measurement at an altitude of 50 m is expected to have a variation of about 0.25 mGal.

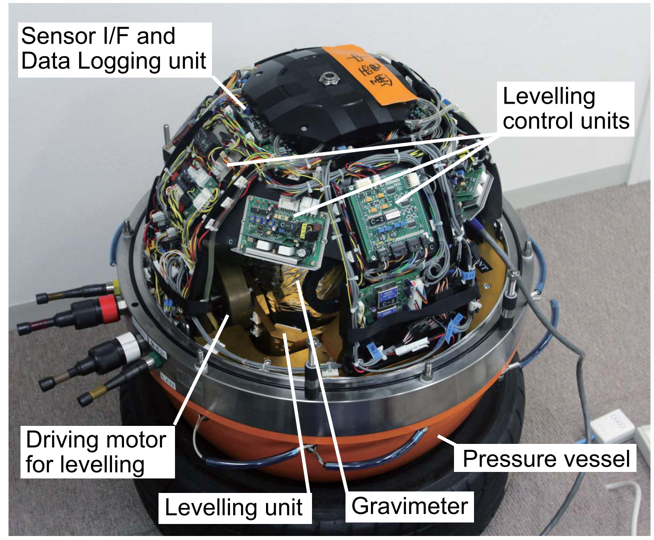

Fig. 2. Photograph of inside of the developed gravimeter. A 2-D forced levelling system is installed in a sphere pressure vessel with a diameter of 50 cm. Developed SI/FDL unit is contained in the same vessel. A heater for the gravimeter must be always turned on to keep a constant temperature.

II. Instruments and Methods

A. Gravimeter

For the underwater measurement of gravity on an AUV, a typical sea surface gravimeter needs to be improved. For example, the sensitivity of a typical gravimeter used for sea surface measurement is not enough, and it is also necessary to modify its mechanical robustness and reduce noise. Micro-g LaCoste S-174 was adopted for the gravimeter of our underwater measurement system. The observation range of the S-174 was modified to ±20 Gal, about 1/10 of the original model. This allows the S-174 to obtain ten times higher sensitivity than the original model. Since the gravimeter is based on the principle of a beam attached to a zero-length spring, the beam must be clamped during transport. The clamping mechanism of the gravimeter can be remotely controlled. The gravity data are continuously digitized with 24-bit resolution and transmitted using serial communication protocol. The sampling rate is approximately 100 Hz. The gravimeter has two orthogonal horizontal accelerometers (Jewell Instruments, LCF-215-0.2G), a pressure meter inside the canister and a thermometer. These data are also digitized and outputted with the gravity data. To acquire high-resolution data, the gravity sensor must be kept at constant temperature (60.4 °C), so we installed the sensor into a thermally insulated metal case. An electrical heater is used to keep the temperature constant. The gravimeter is sensitive to magnetic fields due to a magenetic feedback system. To reduce the effect of changes in the ambient magnetic field, the gravimeter needs a magnetic shield. We provided the metal case for thermal insulation with permalloy as magnetic shielding. After all modifications, we confirmed that the gravimeter has 0.5 mGal/month of drift rate.

B. Levelling System for Gravimeter

The gravimeter must be kept vertical during the measurement of gravity. Therefore, we have developed an original levelling system for the gravimeter. The gravity sensor is installed on a platform that is driven dynamically to keep it horizontal. The rotation shaft on the platform is driven directly by a dc motor. An inertial navigation sensor (an optic fiber gyroscope, IXSEA PHINS) is also mounted on the platform for levelling control. The proportional–integral–derivative method is used for control of the levelling system. Using angle and angular velocity data from the inertial navigation sensor, the system drives the dc motors to keep the platform horizontal. The platform has two horizontal axes, with an angular range of rotation of ±30° in one direction and ±15° in the orthogonal direction.

We usually set the direction with the large angle parallel to the pitch direction of the AUV. The levelling system has a clamping mechanism for protection from large movement: if the angle of the AUV exceeds ±30°, the system clamps the platform immediately. The levelling system is designed to be installed into a spherical pressure vessel made of titanium alloy with a diameter of 50 cm (Fig. 2). The pressure vessel is usable to 4200 m below sea level. We evaluated the performance of the levelling system on a shaking test bed. It was found that the vertical was kept within 0.0004° in a static condition. To minimize the magnetic field, both the gravimeter and dc motors of the levelling system are completely covered with an additional sheet of permalloy.

C. Sensors for Supplement of Gravity Data

Because an underwater vehicle has movement and rotation in all directions, data from the gravimeter need various corrections. We added various sensors to the gravity measurement system. A vertical accelerometer with high precision (Japan Aviation Electronics Industry, Ltd, JA-5 Type III) was installed on the platform of the levelling system to record vertical acceleration, and produces analog output. We also attached three orthogonal accelerometers to the frame of the levelling system to record acceleration of the body of the mobile vehicle. These accelerometers were made by Paroscientific, Inc., and are based on quartz crystal oscillation. Information on position, pitch, and roll angles of the AUV body is transmitted from the mobile vehicle controller via communication lines.

The effect of vertical acceleration of the mobile vehicle must be compensated. Because an accelerometer senses both vertical acceleration and vertical gravity, it is difficult to correct the gravity data by means of an accelerometer alone, so we installed a precise pressure meter with resonant quartz technology (Paroscientific, Inc. 8B series). It has a resolution of better than 1 part per million of maxium measurement value. The pressure meter has digital outputs and their sampling frequency is selectable. We usually choose a frequency of 40 Hz for the observations.

D. Recording and Communication System

The underwater gravity measurement system must receive data from various sensors simultaneously and store them. Timing of data is important for correction of the gravity data. A clock on the underwater vehicle and the recording system are synchronized and a time stamp is added to the sensor data as it is received by the recording system. Communication with the vehicle is also important. During deployment and recovery of an underwater vehicle, the sensor of the gravimeter must be clamped. During stable navigation on profiles, the sensor is unclamped. According to these requirements, we developed a sensor interface and data logging (SI/FDL) unit using a CPU and field-programmable gate array (FPGA) (Fig. 3). Although the first gravimeter system had a sensor interface unit and a data logging unit contained in two separate capsules [5]–[7], the current system has only one unit with both functions in one vessel [11]. The SI/FDL unit uses the Linux operating system, which records data from various sensors simultaneously, communicates with the underwater vehicle, and controls the levelling unit and the gravimeter. The SI/FDL unit also distributes electric power from the mobile vehicle to its various units. The SI/FDL unit has a rubidium clock and appends a time stamp as it receives data. For analog data, a time stamp is added during A/D conversion. The clock in the SI/FDL unit can be synchronized with a clock in a mobile vehicle through a communication function. The data collected by the SI/FDL unit are stored in SD memory cards. The unit has two SD cards and each SD card has identical data as a backup for the other. The SI/FDL unit has an ethernet interface, and we can retrieve the data in the SD cards via this interface through a penetrator without opening the pressure vessel. The ethernet interface is also used for maintenance of the SI/FDL unit. The unit monitors the gravimeter and the levelling system during operation. For example, it clamps the gravimeter and the levelling system immediately using back-up batteries if the power supply is interrupted.

E. Performance of Gravimeter on Levelling System

We conducted gravity measurement experiments to examine the effectiveness of the levelling system and preliminary data processing. The levelling system with the gravimeter was set on a shaking table which simulates motions of pitch and roll. Evaluation was carried out under the conditions that period and amplitude of shaking were 16 s and 7.5°, which was thought to be greater than those expected in actual vehicle motions. We applied two-step low-pass filtering with 1 and 150 s Gaussian filters to the collected data. The filtering widths correspond to a spatial resolution of about 75 m in the case of a vehicle moving at a speed of two knots. The root-mean-square (rms) errors of the collected data were 0.04 and 0.02 mGal for pitch and roll motions, respectively, after processing of the filtering, tilt and earth tide corrections and removal of linear temporal drift [7], [11], [12]. These rms errors are below the minimum resolution required to detect gravity anomalies.

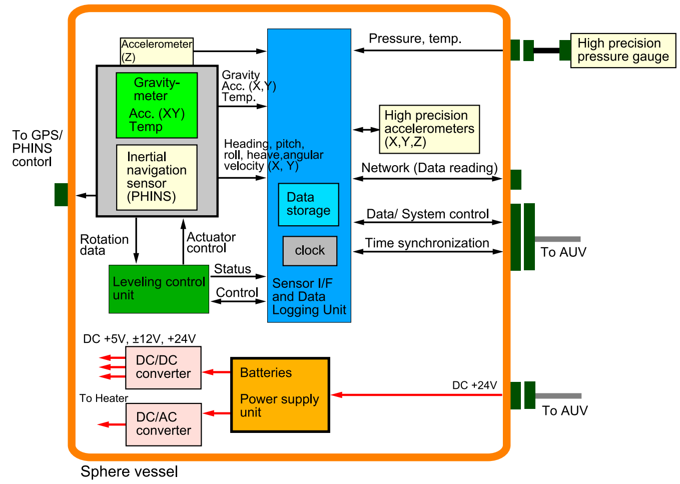

Fig. 3. System block diagram of developed underwater gravity measurement system. The gravity sensor is mounted on developed levelling system with inertial navigation sensor (fiber optic gyroscope). The data from the gravimeter and other sensors for compensation of the gravity data are stored. During the observation, an AUV sends timing and navigation data to the system. The power is supplied from the AUV. The system has back-up batteries for an emergency shutdown.

F. Installation of Gravimeter to AUV

The AUV Urashima, belonging to the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan, was found to be suitable for the platform of our underwater gravity measurement system because of its large payload space for the gravity measurement system and because it allows stable navigation. The Urashima has a length of 10 m, a width of 1.3 m, and a depth rating of 3500 m. Its speed ranges from 0 to 3 knots with an energy source of lithium-ion batteries. To mount the gravity measurement system on the Urashima, we built an installation frame with a vibration isolation system. The installation frame is also useful for transport of the gravity measurement system. Our gravity measurement system was installed in a payload space at the front of the Urashima with the underwater gravity gradiometer (Fig. 4). We also installed a high-precision pressure meter to estimate vertical acceleration in the front payload space. The temperature of the gravimeter can not be controlled when the outside temperature is high, therefore we developed a cooling system for the pressure vessel. Using the cooling system, we kept the gravimeter at constant temperature even in a high temperature environment. We also modified the Urashima for

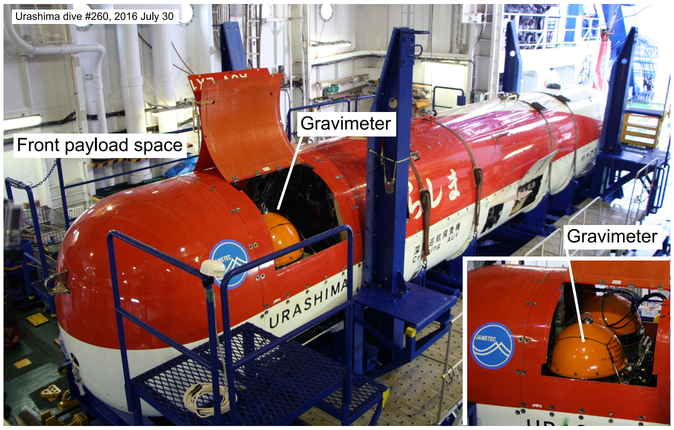

Fig. 4. Gravity measurement system is mounted on a front payload space of the AUV Urashima, JAMSTEC. Stable navigation is possible by using the Urashima. The power for the gravity measurement system is supplied from lithium-ion batteries on the Urashima and communication via the Urashima by acoustics is available.

installation of our gravity measurement system. We made a balance adjustment to the Urashima due to the weight of the gravity system. The power to the gravimeter system, including the heater, is supplied by the Urashima. Electric current was increased because the gravity system needs significant electric power. An acoustic communication system enables control and monitoring of the gravity measurement system during the exercise. Therefore, we modified the acoustic communication system of the Urashima for direct communication between the gravity system (payload) and a control system on the mother ship. When the Urashima detects a problem such as trouble in the controlling software, it initiates an emergency ascent. The Urashima has two modes for navigation, constant depth mode and constant altitude mode. For gravity measurement, vertical acceleration must be as small as possible, hence constant depth mode is more suitable, due to suppression of rolling and pitching of the Urashima during navigation. The Urashima basically navigates by using an inertial system. For more accurate navigation, we measure precise speed of the Urashima using a Doppler velocity log to suppress errors in the inertial system. This hybrid navigation system provides us with a more accurate position of the Urashima in the seawater. Navigation with low position error is important to measure gravity accurately. Position data, and pitch and roll angles are sent to the gravity measurement system via the digital interface at intervals of 1 Hz.

III. Observation and Results

We made our first test exercise in Sagami Bay, southwest of Tokyo, Japan, in September 2012 (Fig. 5). The experimental area had flat topography with a water depth of approximately 1300 m. The first observation aimed to evaluate the underwater gravity measurement system installed on the AUV Urashima. The gravity measurement system communicated with a computer on the mother ship Yokosuka, via an acoustic system. The Urashima made two dives, going out and coming back along a single profile line with a constant speed and a constant depth for each dive. We evaluated the accuracy of the data by comparing data from different tracks after data processing.

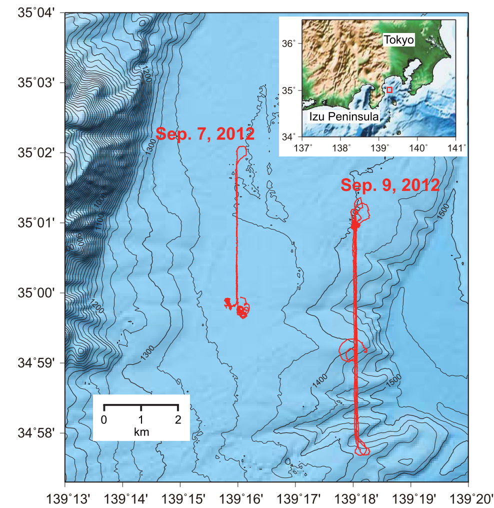

Fig. 5. Position of an area for the first experiment of developed underwater gravity measurement system and tracks of the Urashima during the experiments. The evaluation was performed off the east coast of Izu Peninsula. The first observations were carried out on September 7, 2012 and September 9, 2012.

The first measurement was performed on September 7 along a straight profile with a length of 2 miles, in a south-north direction. The depth of the first profile was 1250 m. The Urashima made one round trip along the profile during the first dive. The second dive was made on September 9 along a straight profile with a length of 3 miles, and a depth of 1300 m, also in a north-south direction. The Urashima navigated in constant depth mode and made two and a half round trips on the profile. The profile for the first dive was laid on smooth seafloor to avoid any large change of gravity along the track, but the second experiment had rough seafloor topography to confirm that the system could detect a gravity change due to topography. The data from the gravimeter and the supplemental data for compensation of the gravity data along both tracks had good quality, and the data were evaluated for the performance of the system.

The obtained gravity data were first low passed to reduce noise. The effect of vertical acceleration calculated from the precise pressure meter data was removed from the gravity data. Next, we made tilt corrections using horizontal accelerometers. Finally, we applied ordinary data processing for onboard gravimeters. The data processing of our underwater gravity measurement system is described in [12] and [13]. The data from each track show good agreement after processing. The standard deviation of the matched track data is approximately 0.1 mGal. In other words, our system is estimated to have a repeatability of 0.1 mGal (Fig. 6). The results from the underwater gravimeter can be compared to that of a surface ship gravimeter. The underwater gravity measurement system recorded more detailed variations of gravity, which we believe to originate from the topography.

The accuracy of the gravity measurement was estimated to be adequate for an exploration of deposits from model calculations. Therefore, the developed underwater gravimeter has been used for mapping of gravity anomalies in seafloor deposits areas around Japan since 2013, resulting in

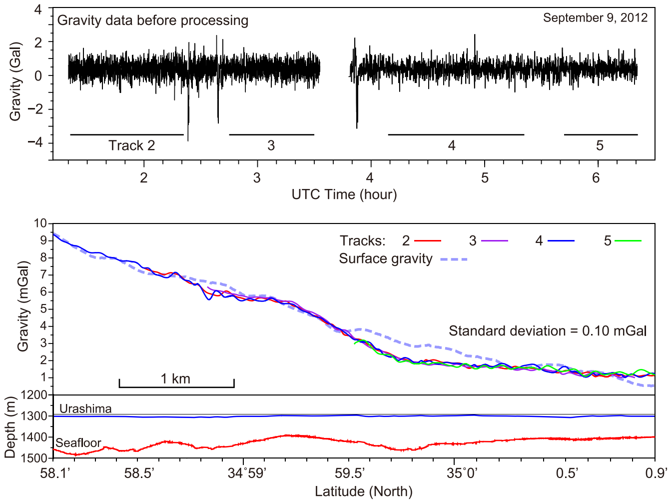

Fig. 6. Gravity data obtained during the field evaluation on (Top) September 9, 2012 and (Bottom) processed gravity data. The gravity data before processing had large noise with amplitude of a few Gal. After noise reduction, the data from each track showed good agreement with other tracks. The standard deviation of the data is approximately 0.1 mGal. The results from the underwater gravimeter are compared to that of a surface ship gravimeter.

detailed gravity maps in the areas where seafloor deposits exist [13], [14]. In 2017, we again carried out an observation using our underwater gravimeter in Sagami Bay, and reconfirmed that our system has an accuracy of 0.1 mGal during constant depth navigation.

IV. Summary

We have developed an underwater gravity measurement system installed on an AUV for exploration of seafloor ore deposits. A modified marine gravity sensor was used, and we added a levelling system, a recording system and a communication system. A spherical titanium vessel with a diameter of 50 cm contains the system. The underwater gravity measurement system requires a resolution of approximately 0.1 mGal effectively to detect deposits below the seafloor. We obtained an error estimate for our gravity measurements of less than 0.04 mGal based on an on-land shake test. We chose the AUV Urashima, JAMSTEC, for our underwater gravity measurement. The evaluation of the system was carried out in September 2012 in Sagami Bay, Japan. The Urashima made a round trip along a straight profile at constant speed and constant depth. The repeatability of the obtained gravity data is estimated to be 0.1 mGal after data processing. Our system can survey a wide area quickly with a high resolution, which is required to obtain a detailed structure below the seafloor.

Acknowledgment

The authors would like to thank the captain and crew of the M/V Yokosuka, JAMSTEC, Yokosuka, Japan, for success in the experiments. They would also like to thank the skillful maneuvers of the AUV by the Urashima Team, JAMSTEC. Comments from Dr. A. Van Horne and anonymous reviewers were useful in improving the manuscript.

References

[1] H. Fujimoto *et al.*, "Underwater gravimeter on board the R-One robot," in *Proc. Int. Symp. Underwater Technol.*, Tokyo, Japan, May 2000, p. 297-300, doi: 10.1109/UT.2000.852559.

[2] G. S. Sasagawa, W. Crawford, O. Eiken, S. Nooner, T. Stenvold, and M. A. Zumberge, "A new sea-floor gravimeter," *Geophysics*, vol. 68, no. 2, pp. 544–553, 2003.

[3] M. Zumberge, H. Alnes, O. Eiken, G. Sasagawa, and T. Stenvold, "Precision of seafloor gravity and pressure measurements for reservoir monitoring," *Geophysics*, vol. 73, no. 6, pp. WA133–WA141, doi: 10.1190/1.2976777.

[4] H. Fujimoto *et al.*, "Remodeling of an ocean bottom gravimeter and littoral seafloor gravimetry—Toward the seamless gravimetry on land and seafloor," *J. Geodetic Soc. Japan*, vol. 55, no. 3, pp. 325–339, 2009.

[5] H. Fujimoto *et al.*, "Development of a hybrid gravimeter system onboard an underwater vehicle," in *Proc. IEEE Symp. Underwater Technol. Workshop Sci. Submarine Cables Related Technol.*, Tokyo, Japan, Apr. 2011, pp. 1–3, doi: 10.1109/UT.2011.5774162.

[6] T. Kanazawa *et al.*, "New underwater hybrid gravity measurement system consisting of a gravimeter and a gradiometer," in *Proc. 22nd Ocean Eng. Symp.*, Tokyo, Japan, Mar. 2011, pp. 17–18.

[7] M. Shinohara *et al.*, "Development of an underwater gravimeter and the first observation by using autonomous underwater vehicle," in *Proc. IEEE Int. Underwater Technol. Symp. (UT)*, Tokyo, Japan, Mar. 2013, pp. 1–6, doi: 10.1109/UT.2013.6519864.

[8] J. C. Kinsey, M. A. Tivey, and D. R. Yoerger, "Dynamics and navigation of autonomous underwater vehicles for submarine gravity surveying," *Gephysics*, vol. 78, no. 3, pp. G55–G68, 2013, doi: 10.1190/GEO2012-0181.1.

[9] D. DiFrancesco, A. Grierson, D. Kaputa, and T. Meyer, "Gravity gradiometer systems–advances and challenges," *Geophy. Pros.*, vol. 57, no. 4, pp. 615–623, 2009, doi: 10.1111/j.1365-2478.2008.00764.x.

[10] A. Araya *et al.*, "Development and demonstration of a gravity gradiometer onboard an autonomous underwater vehicle for detecting massive subseafloor deposits," *Ocean Eng.*, vol. 105, pp. 64–71, Sep. 2015, doi: 10.1016/j.oceaneng.2015.06.008.

[11] M. Shinohara *et al.*, "Development of an underwater gravity measurement system using autonomous underwater vehicle for exploration of seafloor deposits," in *Proc. OCEANS-Genova*, Genoa, Genova, May 2015, pp. 1–7, doi: 10.1109/OCEANS-Genova.2015.7271487.

[12] T. Ishihara *et al.*, "Development of an underwater gravity measurement system with autonomous underwater vehicle for marine mineral exploration," in *Proc. Techno-Ocean (Techno-Ocean)*, Kobe, Japan, Oct. 2016, pp. 127–133, doi: 10.1109/Techno-Ocean.2016.7890633.

[13] T. Ishihara *et al.*, "High-resolution gravity measurement aboard an autonomous underwater vehicle," *Geophysics*, to be published, doi: 10.1190/GEO2018-0090.1

[14] M. Shinohara *et al.*, "Mapping of seafloor gravity anomalies by underwater gravity measurement system using autonomous underwater vehicle for exploration of seafloor deposits," in *Proc. OCEANS-Anchorage*, Anchorage, AK, USA, Sep. 2017, pp. 1–6.