Development of Optical Inspection Technology for Deep-Sea Floor using Fluorescent Observation Method

Masahiko Sasano
Underwater Technology Department
National Maritime Research Institute
6-38-1 Shinkawa, Mitaka, Tokyo, Japan
sasano@nmri.go.jp

Yasuharu Nakajima
Ocean Engineering Department
National Maritime Research Institute
6-38-1 Shinkawa, Mitaka, Tokyo, Japan

Joji Yamamoto
Ocean Engineering Department
National Maritime Research Institute*
6-38-1 Shinkawa, Mitaka, Tokyo, Japan
(*current affiliation: JOGMEC)

Yasuo Furushima
R&D Center for Submarine Resources,
Japan Agency for Marine-Earth Science and Technology
2-15 Natsushima-cho, Yokosuka, Kanagawa, Japan

***Abstract*—We developed a pressure tight ultra violet (UV) light-emitting diode (LED) light for deep-sea floor optical imaging. It was confirmed by deep-sea in situ observation that many deep-sea organisms show fluorescent properties, and the fluorescent colors are unique for each deep-sea species. Additionally, we developed a pressure tight violet-laser-induced spectrometer for deep-sea remote inspection. It was confirmed by laboratory experiments that laser-induced fluorescence from oil in water shows characteristic fluorescent spectrum for each oil type. Fluorescent observation systems are expected to be useful tools for deep-sea floor inspection by mounting them on a remotely operated vehicle (ROV) or autonomous underwater vehicle (AUV).**

Keywords—LED, laser; spectrometer; deep-sea; fluorescence

I. Introduction

In recent years, deep-sea floor drilling technologies have been developed for oil and natural gas wells, and offshore rigs have been established in many of the world's oceans [1]. In addition, deep-sea mining surveys are operated for the development of hydrothermal deposits, especially in the Okinawa Trough, Japan [2]. The importance of in situ observation technologies for the deep-sea floor is increasing.

It is difficult to use radar and infrared cameras in the deep oceans because of the severe attenuation of radio and infrared rays in ocean water [3]. Also, because it is difficult to maintain the directionality of sound in water, resolution is a challenge for sonar observations [4]. In this respect, visible light is capable of high-resolution observation as long as the target is within a range of approximately 10 m. Also, it is possible to observe the optical properties of an object remotely by spectroscopic investigation using an excitation light and a spectrometer.

In this study, we developed a fluorescence imaging system and a fluorescence spectrometer system for deep-sea floor inspection.

II. Fluorescent Images

The deep-sea floor is a dark environment, and illumination is necessary for image sensing. In other words, background light is negligible, which is the appropriate condition for fluorescence observation. In addition, many deep-sea floor organisms use self-generated bioluminescence [5], while some of them show fluorescent properties. It is expected that the fluorescent imaging method will be useful for environmental assessment of the deep-sea floor.

A. Pressure Tight UV LED Light

A pressure tight UV LED light system was developed for in situ fluorescence imaging on deep-sea floors. The center wavelength of LED emissions is 385 nm with a wavelength distribution of 10 nm full-width at half-maximum, the illumination power is approximately 15 W using 12 high-power UV LEDs (Nichia NC4U134A), and the spread angle of UV illumination is approximately 30 degrees by half angles. The maximum withstanding depth of this system is 3,000 m. The specifications of this system are shown in Table I.

978-0-933957-43-5 ©2015 MTS

TABLE I. SPECIFICATIONS OF THE UV-LED LIGHT

Specifications	
Center Wavelength	385 nm
Wavelength FWHM	10 nm
UV Intensity	15 W (12 LEDs)
Spread Angle	±30 deg
Consumed Power	15 V, 90 W
Vessel Size	D 200 mm × L 450 mm
Window Size	D 150 mm (Acryl)
Weight	18 kg (in Air), 9 kg (in Water)
Withstand Depth	3,000 m (max)

B. Deep-sea Observation by ROV

The UV LED light system was installed on the JAMSTEC "Hyper-Dolphin" remotely operated vehicle (ROV) on Nov.24, 2013, and it dived into the Iheya North field, Okinawa Trough, Japan. The seafloor depth was 990 m, and many deep-sea organisms were distributed near hydrothermal vents. The Hyper-Dolphin onboard cameras were used to record fluorescent images. Since the UV LED light was outside the wavelength sensitive range of the camera, the elastic scattering of UV LED light did not affect the video images despite the lack of optical filters on the camera.

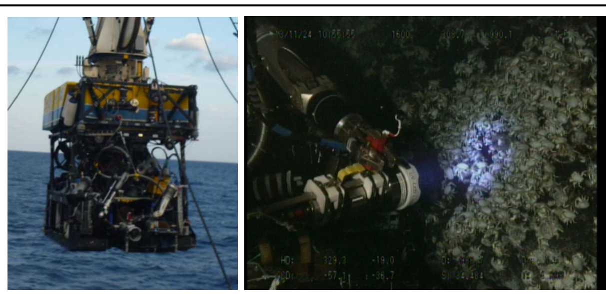

Fig. 1. Photos of "Hyper-Dolphin" ROV (left) and deep-sea floor in situ observation by UV LED light (right).

C. Deep-sea Floor Fluorescent Images

An example of a fluorescent image of the deep-sea floor near a hydrothermal vent is shown in Fig. 2. It is possible to distinguish the fluorescent colors of hydrothermal vent galatheid crabs, hydrothermal vent shrimp, and deep-sea mussels (i.e., Bathymodiolus platifrons). The color-enhanced photo is shown in Fig. 3, which was converted using Adobe PhotoShop Elements 9, and the color difference between the three species is noticeably clear. These results imply that bio-fluorescent characteristics could be applied to the in situ observation of deep-sea organisms and to environmental assessments.

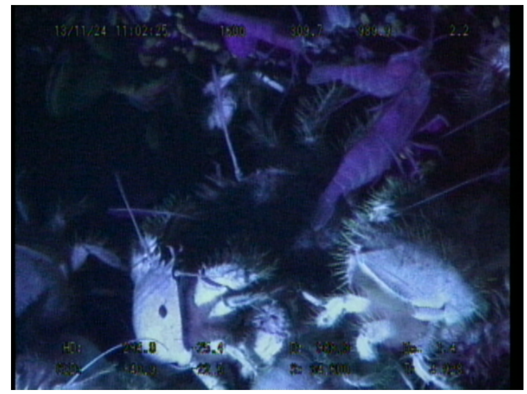

Fig. 2. An example of deep-sea floor fluorescent images.

Fig. 3. An example of deep-sea floor fluorescent images, color-enhanced using Adobe Photoshop Elements 9.

III. FLUORESCENT SPECTRUM

Because fluorescence is stimulated by the optical characteristics of the molecular structure of the target, there would be spectral features of the target even without structural features appearing on the fluorescent images. In particular, oils often show the fluorescence under excitation light, which varies depending on the type of oil [6]. It is expected that oil-type information can be obtained using a laser-induced spectrometer in the deep sea. In addition, the water Raman scattering of light from seawater will be observed by the laser-induced spectrometer [7], but its peak in the spectrum is sharp, and it is possible to distinguish the water Raman signal from the oil fluorescence signal.

A. Pressure Tight Viole- laser-induced Spectrometer

A pressure tight continuous wave (CW) violet-laser-induced spectrometer system was developed for in situ remote spectral observations on the deep-sea floor. The laser wavelength is 405 nm in consideration of the transmittance in seawater. The receiver comprises of a reflecting mirror with a diameter of 110 mm, optical sharp cut filter with a wavelength of 407 nm, optical fiber cable with a core diameter of 0.4 mm, and a spectrometer with a rear-entrance-type CCD (Ocean

Optics QE65Pro). The measurement range of the spectral wavelength is 400-760 nm, and the wavelength resolution is approximately 1.2 nm.

An overview photo of the system is shown in Fig.4, and its specifications are shown in Table II.

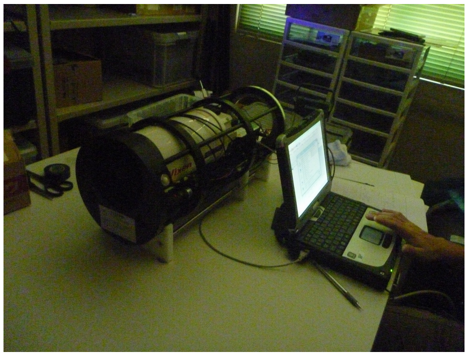

Fig. 4. Photo of the CW violet-laser-induced spectrometer (without a pressure tight vessel).

TABLE II. SPECIFICATIONS OF THE CW VIOLET LASER INDUCED SPECTROMETER

Specifications	
Laser Wavelength	405 nm
Laser Intensity	500 mW × 2
Laser Spread Angle	2-3 deg (adjustable)
Collecting Mirror Diameter	110 mm
Spectrometer Range	400-760 nm
Spectrometer Resolution	1.2 nm
Consumed Power	24 V, 10 W
Pressure Vessel Size	D 260 mm × L710 mm (Al alloy)
Window Size	D 190 mm (Acryl)
Weight	42 kg (in Air), -15 kg (in Water)
Withstand Depth	3,000 m (max)

B. Transmittance of Viole-laser-induced Fluorescence

The observational range of the laser-induced fluorescence spectrometer depends on the round-trip transmittance of light in the seawater, size of the target in the laser footprint and receiver field of view, and fluorescence efficiency of the target. In this system, a violet laser (wavelength 405 nm) was chosen as the excitation light to improve transmittance, although it is a relatively long wavelength for fluorescence observation.

To verify the observational range of this system, a simple test was conducted in a test basin. Fluorescent images were recorded at various distances (4.0, 5.5, 7.0, 8.5, 10.0, and 11.0 m) with CW violet laser excitation and targets of pseudo-coral models containing blue, green, and red fluorescence agents. The test basin was filled with clear fresh water, and an ordinary video camera (Canon HF M32) was used for image recording. The recorded fluorescence images are shown in Fig.5. The observable distance is approximately 10 m in this case.

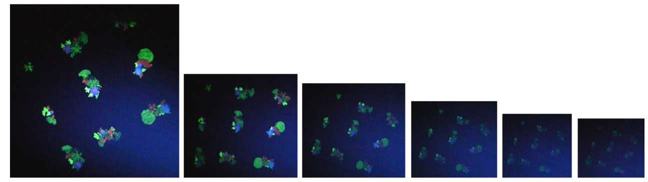

Fig. 5. Transmittance test of CW violet-laser-induced fluorescence at various distance (4.0, 5.5, 7.0, 8.5, 10.0, and 11.0 m) using fluorescent Images in the test basin (target: pseudo-coral models with fluorescence agents).

C. Oil Fluorescent Spectrum

A laser-induced spectrometric observation was tested in a laboratory. The spectrometer system was set to a distance of 4 m from the target. Three types of samples were used as targets: heavy fuel oil, diesel oil, and natural water. Each target was sealed in a test tube of 2.5 cm diameter and 9.0 cm length and was set in a water-filled glass aquarium. The laser path length in water was approximately 40 cm. A photo of the target (heavy fuel oil) is shown in Fig.6.

The obtained spectra of the three samples are shown in Fig.7. The integration time for each spectral observation was 10 seconds. The fluorescent intensity of heavy fuel oil is stronger than of diesel oil, and the fluorescence spectra of heavy fuel oil is distributed on the shorter wavelength side than that of diesel oil, in the case of 405 nm laser excitation. In addition, water Raman light scattering from the tap water in the aquarium can be seen in the vicinity of 475 nm. It is distinguishable from the oil fluorescence.

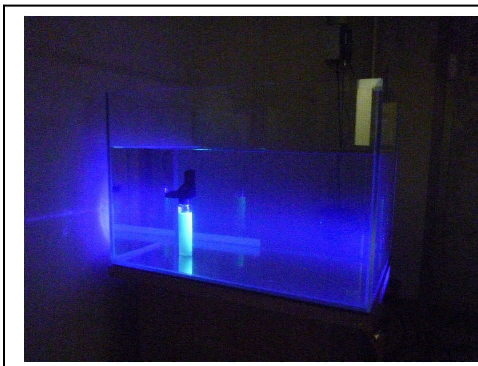

Fig. 6. Photo of violet-laser-induced sample oil (heavy fuel oil in 25 mm × 90 mm cylinder) in the water-filled aquarium.

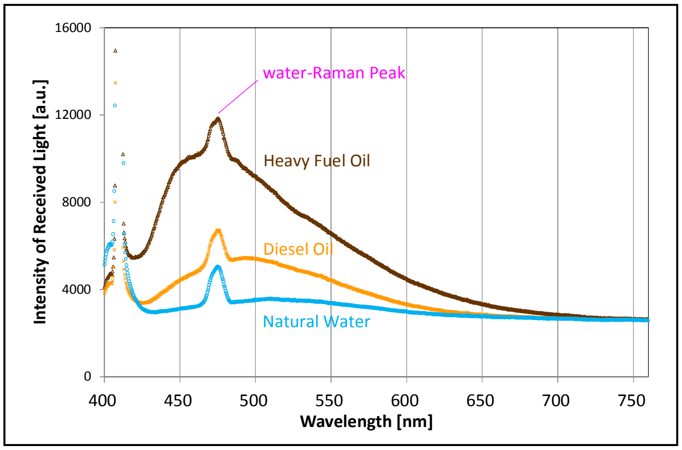

Fig. 7. The violet-laser-induced spectrum of heavy fuel oil, diesel oil, and natural water in an aquarium (target size 25 mm × 90 mm). The spectrometer system was set at 4 m from the target, the path length in water was 40 cm, and the integration time was 10 seconds. The peaks at 475 nm in the spectrum are water Raman signals.

IV. SUMMARY

We developed a fluorescent imaging system and a fluorescence spectrometer system for the inspection of deep-sea floor to a maximum depth of 3,000 m. These systems are useful for in situ observation for biological assessment and oil type detection. In the future, these techniques might be applied not only to deep-sea inspections of organisms or oils, but also to mineral ore identification, hydrothermal plume inspection, methane-hydrate detection, etc.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number 24360365. The development of the pressure tight vessel with a large observation window was supported by the Cross-ministerial Strategic Innovation Promotion Program (SIP) "Next-generation technology for ocean resources exploration." The authors are also grateful to Prof. B. Thornton at the University of Tokyo and the Hyper-Dolphin team at JAMSTEC for the deep-sea fluorescence observations.

REFERENCES

[1] International Energy Agency report, "Resources to Reserces 2013," 2013.

[2] N.Masuda, "Challenges toward the sea-floor massive sulfide mining with more advanced technologies," UT 2011 IEEE Symposium, 2011 .

[3] G.M.Hale and M.R.Querry, "Optical Constants of Water in the 200-nm to 200-um Wavelength Region," Appl. Opt. vol. 12, pp. 555-563, 1973.

[4] R.E.Hansen, "Synthetic Aperture Sonar Technology Review," Marine Tech. Soc. J., vol. 47, pp. 117-127, 2013

[5] S.H.D.Haddock, M.A.Moline, and J.F.Case, "Bioluminescence in the Sea," Annu. Rev. Mar. Sci. 2010, pp. 443–493, 2010.

[6] P.Camagni, A.Colombo, C.Koechler, N.Omenetto, P.Qi, and G.Rossi, "Fluorescence response of mineral oils: spectral yield vs absorption and decay time," Appl. Opt. vol.30, pp. 26-35, 1991.

[7] J.S.Bartlett, K.J.Voss, S.Sathyendranath, and A.Vodacek, "Raman scattering by pure water and seawater," Appl. Opt. vol. 37, pp. 3324-3332, 1998.